

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

PERKIN-ELMER
AEROSPACE DIVISION

NASA CR-
147535

SPACE SHUTTLE

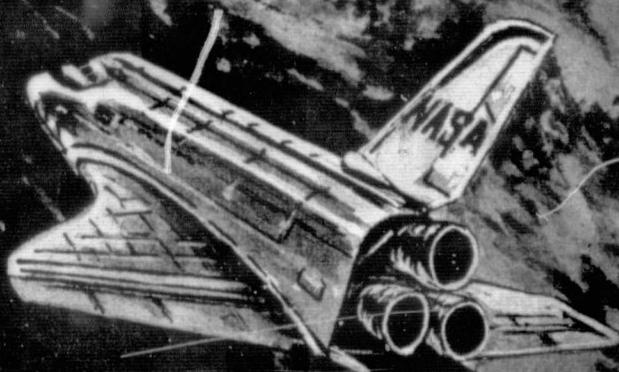
**DEVELOPMENT OF A
DRIVE SYSTEM FOR
A SEQUENTIAL
SPACE CAMERA
FINAL REPORT**

(NASA-CR-147535) DEVELOPMENT OF A DRIVE
SYSTEM FOR A SEQUENTIAL SPACE CAMERA Final
Report (Perkin-Elmer Corp.) 82 p HC \$5.00

CSCl 14E

G3/35
Unclass
25273

N76-22510



THE PERKIN-ELMER CORPORATION

AEROSPACE DIVISION

2771 North Garey Avenue, Pomona, California 91767

FINAL REPORT

DEVELOPMENT OF A DRIVE SYSTEM
FOR A SEQUENTIAL SPACE CAMERA

by

James T. Sharpsteen, Curtis D. Solheim,
Louis J. Stoap

March 1976

Perkin-Elmer SPO 30352

NASA Contract Number NAS9-14573

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Johnson Space Center
Houston, Texas 77058

TABLE OF CONTENTS

| | <u>Page</u> |
|---|-------------|
| 1. INTRODUCTION | 1-1 |
| 2. CAMERA DRIVE REQUIREMENTS, AND OBJECTIVES OF THE STUDY | 2-1 |
| 3. SUITABLE MOTOR TYPES | 3-1 |
| 4. SYSTEM APPROACHES | 4-1 |
| 4.1 Single Motor Drive System | 4-1 |
| 4.2 Two Motor Drive Approaches | 4-9 |
| 5. SYSTEM BREADBOARD | 5-1 |
| 5.1 Mechanical Description | 5-1 |
| 5.2 Electronics Description | 5-9 |
| 6. SUMMARY AND CONCLUSIONS | 6-1 |
| 7. RECOMMENDATIONS | 7-1 |
| APPENDIX A - BRUSHLESS DC MOTORS | A-1 |
| APPENDIX B - SINGLE MOTOR DRIVE | B-1 |

LIST OF ILLUSTRATIONS

| <u>Figure</u> | | <u>Page</u> |
|---------------|---|-------------|
| 2-1 | Drive Configuration for a Typical 16 mm Sequential Space Camera (DAC) | 2-2 |
| 2-2 | Inertial and Frictional Loads for a Typical 16 mm Sequential Space Camera (DAC) | 2-4 |
| 3-1 | Commutation of a Three Phase Delta Wound Brushless DC Motor | 3-4 |
| 3-2 | Commutation Waveforms for a Three Phase Delta Wound Brushless DC Motor | 3-5 |
| 3-3 | Simplified Schematic for Three Phase Delta Brushless DC Motor | 3-7 |
| 3-4 | Commutation of a Two Phase Brushless DC Motor | 3-8 |

LIST OF ILLUSTRATIONS (Continued)

| <u>Figure</u> | | <u>Page</u> |
|---------------|--|-------------|
| 3-5 | Commutation Waveforms for a Two Phase Brushless DC Motor | 3-9 |
| 3-6 | Simplified Schematic for a Two Phase Brushless DC Motor | 3-10 |
| 4-1 | Development of Approaches | 4-2 |
| 4-2 | Shutter and Claw Motion Compared with Time for Various Combinations of Steps and Stepping Rates for a 15° Stepper Motor Camera Drive | 4-4 |
| 4-3 | Transition Torque Requirements from Table 4-1 Compared with Stepper Motor Characteristics | 4-8 |
| 4-4 | Shutter Control with AEC, Mechanical Subsystem | 4-10 |
| 4-5 | Transition Torque Requirements from Table 4-2 Compared with Stepper Motor Characteristics | 4-13 |
| 4-6 | One Piece, Three Opening Shutter for 15° Stepper Motor | 4-16 |
| 4-7 | One Piece Shutter, Two Step Approach | 4-19 |
| 4-8 | One Piece Shutter, Two Step Approach Shutter Travel and Inertia vs Shutter Diameter | 4-20 |
| 4-9 | One Piece, 2 Step Shutter Configurations for Direct Drive from 45° Stepper | 4-21 |
| 4-10 | Friction Load (Torque) on Motor Output Shaft | 4-23 |
| 4-11 | Breadboard Claw Mechanism | 4-24 |
| 4-12 | Transition Torque Requirements from Table 4-5 Compared with Stepper Motor Characteristics | 4-26 |
| 5-1 | Shutter Blade | 5-3 |
| 5-2 | Comparison of Various Materials (See Figure 5-1) | 5-4 |
| 5-3 | Shutter Drive | 5-6 |
| 5-4 | Timing Diagrams for Shutter Position Detector Outputs | 5-7 |
| 5-5 | Shutter Position Detector | 5-8 |
| 5-6 | Motor and Gearing Installations | 5-10 |
| 5-7 | Shutter Speed Test Fixture | 5-11 |
| 5-8 | Film and Shutter Drive Functional Block Diagram | 5-12 |
| 5-9 | Electronic Dual Motor Drive Schematic | 5-13 |
| 5-10 | Timing Diagram - Shutter Drive (1/125 Second Exposure) | 5-15 |
| 5-11 | Timing Diagram - Shutter Drive (1/60 Second Exposure) | 5-16 |
| 5-12 | Timing Diagram - Shutter Drive (1/500 Second Exposure) | 5-18 |

LIST OF ILLUSTRATIONS (Concluded)

| <u>Figure</u> | | <u>Page</u> |
|---------------|---|-------------|
| A-1 | Brushless DC Motor Characteristic Performance Curves | A-2 |
| B-1 | Four Stepper Motor Timing Methods for Accomplishing the Film Pull-Down Cycle | B-2 |
| B-2 | Single Motor Drive Functional Block Diagram | B-4 |

LIST OF TABLES

| <u>Table</u> | | <u>Page</u> |
|--------------|--|-------------|
| 3-1 | Stepper Motors Used or Considered in Study | 3-2 |
| 4-1 | Total Camera System Torque Requirements for Stepping Rate Transitions | 4-7 |
| 4-2 | Two Piece Shutter Torque Requirements for Stepping Rate Transitions | 4-12 |
| 4-3 | Relation of Exposure Time to Step Rate and Shutter Angle For One Piece, Three Opening Shutter Direct Connected to 15° Stepper Motor | 4-15 |
| 4-4 | Relation of Maximum Stepping Rate and Shutter/Aperture Margin to Shutter Travel, For One Piece, Two Opening Shutter on a 15° Stepper Motor | 4-18 |
| 4-5 | Breadboard Claw Mechanism Torque Requirements for Stepping Rate Transitions | 4-25 |
| 7-1 | Comparison Factors Between the Two Most Favorable Approaches | 7-2 |

1. INTRODUCTION

This document is the final report for the development of a drive system for a sequential space camera, under NASA Contract No. NAS9-14573, conducted by the Perkin-Elmer Corporation, Aerospace Division, Pomona, California for the Johnson Space Center. The analysis portion of the study, and the preliminary testing of motors and mechanisms prior to breadboard construction were reported under Phase I of the contract, Trade-Off Analysis and Design, which is also included in this report.

At the time of the Phase I report, one approach was selected which demonstrated the most promise in meeting the objectives of the study. This approach uses an electronically commutated dc motor for driving the camera claw and magazine, and a stepper motor for driving the shutter with the two motors synchronized electrically. Subsequent tests on the breadboard positively proved the concept, but further development beyond this study should be done before making the commitment to final design.

The breadboard testing also established that the electronically commutated motor can control speed over a wide dynamic range, and has a high torque capability for accelerating loads. This performance suggested the possibility of eliminating the clutch from the system while retaining all of the other mechanical features of the DAC, if the requirement for independent shutter speeds and frame rates can be removed. Therefore, as a final step in the study, the breadboard shutter and shutter drive were returned to the original DAC configuration, while retaining the brushless dc motor drive.

When this report was being prepared, some time remained until the scheduled completion date of the study. This report includes a discussion of breadboard results as of this date. Significant information obtained from further breadboard testing between now and contract completion will be published in an addendum to this report.

2. CAMERA DRIVE REQUIREMENTS, AND OBJECTIVES OF THE STUDY

The design requirements for the breadboard are covered both in the contract and the Perkin-Elmer Aerospace Division (ASD) proposal. The majority of these requirements are related to the type of camera. The performance requirements are essentially those of the 16 mm DAC, as follows:

1. Frame rates of 2, 6, 12, and 24 fps, and single exposures (pulse mode), with frame rate accuracies of 1% or better.
2. Shutter speeds of 1/1000 second to 1/60 second, with exposure jitter from frame to frame not to exceed 2%. Shutter speed accuracy to be $\pm 10\%$ or better.
3. The drive system shall be capable of transporting up to 400 feet of film without requiring auxiliary motors.
4. Shutter speeds and frame rates shall be independent.
5. The system shall operate from a nominal 28 V dc supply which may vary from 22 to 35 V dc. The design goal for peak current is 300 milliamperes.

The requirements that represent major departures from the DAC are presented below:

6. All motors shall be of the brushless dc type.
7. The drive system shall not use a clutch.
8. The drive system may use one or two motors (but not more than two).
9. One of the criterion for selection of the drive system approach is its ability to interface with the Automatic Exposure Control (AEC) concepts developed under contract NAS9-12790.

There are a number of other design requirements specified that are related primarily to good camera design rather than specifically to a brushless motor camera design. These will not be repeated here because they are not particularly relevant to this phase of the study.

The various functions in the camera that are motor driven and which must be considered in the motor drive study are shown in Figure 2-1, which uses the DAC as an example. In the DAC, these functions are all driven by a single motor

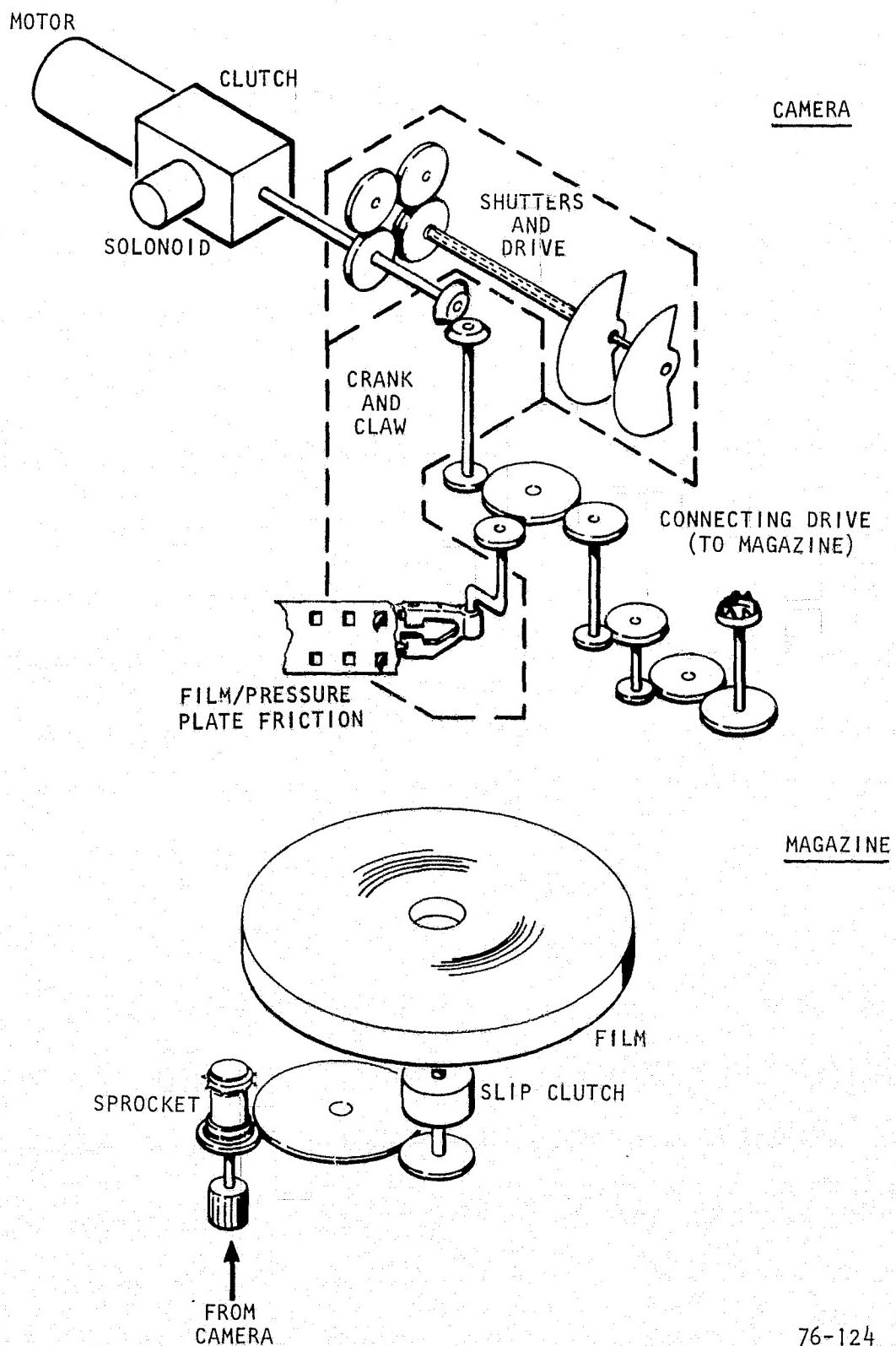


FIGURE 2-1. Drive Configuration for a Typical 16 mm Sequential Space Camera (DAC)

through a solenoid actuated clutch. The inertial and frictional loads for these functions (estimated for the DAC) are shown in Figure 2-2. Since the Statement of Work allows the use of two motors in the drive system, these functions could be separated and grouped in various ways between the two motors. The loads shown in Figure 2-2 are for reference only, since redesign and regrouping should allow these to be somewhat reduced. The study to date has examined these options, and several suboptions which have come to light during the study, based on information which has been assembled on the various types of brushless motors and their capabilities.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

| FUNCTION | SINGLE MOTOR DRIVE | DUAL MOTOR DRIVE | | |
|--|---|--|---|--|
| | | MOTOR 1 1.37 GM-CM ² INERTIA | MOTOR 1 1.37 GM-CM ² INERTIA | MOTOR 1 1.67 GM-CM ² INERTIA |
| SHUTTER (1.37 GM-CM ² INERTIA) | ONE MOTOR 2.83 GM-CM ² INERTIA | | | |
| CRANK AND CLAW (0.95 GM-CM ² INERTIA) | | MOTOR 1 2.32 GM-CM ² INERTIA | MOTOR 2 | |
| FILM PRESSURE PLATE (67 GM-CM FRICTION) | 90 GM-CM FRICTION (MAX) | 67 GM-CM FRICTION | | MOTOR 2 |
| REGISTRATION PIN (0.3 GM-CM ² INERTIA) | | | | MOTOR 1 |
| CONNECTING DRIVE (0.406 GM-CM ² INERTIA) | | | | |
| SPROCKETS (0.1 GM-CM ² INERTIA) | | | 1.46 GM-CM ² INERTIA 90 GM-CM FRICTION (MAX) | MOTOR 2 |
| FILM TAKE-UP (INCL FILM) (23 GM-CM, FRICTION) | | MOTOR 2 0.1 GM-CM ² INERTIA 23 GM-CM FRICTION | * | 0.1 GM-CM ² INERTIA 90 GM-CM FRICTION (MAX) |

NOTE: FOR COMPARISON, ALL INERTIAS AND TORQUES ARE REFERRED TO
A SPEED OF 1 REVOLUTION PER FILM FRAME

*CHANGED SINCE THE PHASE I REPORT

FIGURE 2-2. Inertial and Frictional Loads for
a Typical 16 mm Sequential Space Camera (DAC)

3. SUITABLE MOTOR TYPES

Descriptions of the four basic types of brushless dc motors were included in the ASD proposal. This discussion is also included in Appendix A of this report for reference. The results of further investigation since the start of the study contract, as applicable to camera drive systems, is presented in the following paragraphs.

The two types of brushless dc motors that have been actively pursued in this study are the stepper and the electronically commutated motor. The ac motor/inverter has not been studied further due to its size and relative inefficiency. The limited rotation dc torquer, although a possible candidate for a push-pull type operation on the shutter, has also not been studied further due to the difficulties it would present in obtaining accurate positioning.

As the discussion in the following sections will show, the stepper motor is apparently an excellent candidate for driving a fixed opening (or openings) single blade shutter. The performance of stepper motors naturally varies with the electrical design. Variations include permanent magnet and variable reluctance types, three and four phase versions, winding resistances, and variations in design details between manufacturers. For the purpose of analysis in this study, motor configurations were selected which give the best performance in terms of dynamic torque versus stepping rate. These are shown on Table 3-1, which also shows the stepper motors that were used or will be used in breadboard testing. All analyses were based on two phase excitation, which gives higher torques than one phase excitation.

Due to its relative inefficiency when operating in an open loop configuration, the stepper motor may not be the best selection for providing film drive. The electronically commutated motor will apparently provide the linearity and efficiency characteristics of the conventional dc motor without the problems associated with brushes. Thus, this type motor has been given serious consideration for providing the claw and magazine drive.

Since the stepper motor is described rather extensively in Appendix A, that information will not be repeated here. However, the following information is provided as a supplement to Appendix A relative to the electronically commutated motor.

A brushless dc motor duplicates the performance characteristics of a dc motor only if properly commutated. Proper commutation involves excitation of the stator windings in a sequence that keeps the field produced by the stator

TABLE 3-1. Stepper Motors Used or Considered in Study

| Size | Model* | Step Angle | Type | Winding Resistance (Ohms) | Test |
|------|---------|------------|-------|---------------------------|--------------------------------------|
| 8 | 08R-01 | 15° | VR/4Ø | 100 | Shutter (Fig 4-6) Claw (Fig 4-11) |
| 8 | 08M-01 | 45° | PM/4Ø | 65 | Shutter (Fig 4-7) |
| 8 | 08P-08A | 90° | PM/4Ø | 55 | Shutter (Fig 5-3) |
| 11 | 11R-01 | 15° | VR/4Ø | 55 | |
| 11 | 11M-01 | 45° | PM/4Ø | 45 | |
| 15 | 15R-01 | 15° | VR/4Ø | 35 | |

*COMPUTER DEVICES OF CALIFORNIA DESIGNATION

approximately 90 electrical degrees ahead of the rotor field. Stated another way, the voltage applied to the windings must be in phase with the back EMF produced by those windings. As stated above, some type of position feedback is necessary to accomplish brushless dc motor commutation.

LED phototransistor feedback is used in the following example. In this technique a wheel with windows of the proper arc length are rotated between an LED and a phototransistor. The phototransistor is turned on when a window is present, and off when a window is not present. The number of LED phototransistor pairs that are required depends on the winding configuration and the commutation plan. In the following schemes the number of electronic devices has been minimized for the winding configurations chosen.

Other types of feedback are possible, but the LED phototransistor technique results in the simplest electronic system.

A three phase delta system has the lowest ripple torque of the simple brushless systems, about seven percent average to peak. For this reason, it is chosen for the first example.

The torque output of the motor with no commutation is shown in Figure 3-1A as a function of rotor position (in electrical degrees). A curve is drawn for each of the three phases. The peaks of these sinusoidal torque curves are equal to the line currents supplied to the windings times the torque sensitivity of the motor.

Commutation must take place in a way that will supply current to the phase which is operating within 30 electrical degrees of its peak. The current polarity must be reversed for negative torque peaks. If this is done, the torque compared with angle graph shown in Figure 3-1C is the result.

The table in Figure 3-1B shows the proper polarity of voltage that will be applied to the terminals for each segment of commutation. Note that the direction of rotation can be reversed by reversing the polarity of the two terminals in each segment.

The next step is to develop the information necessary for applying the voltage to the proper terminals at the proper time. The outputs of three sensors, which are spaced 60 electrical degrees apart and which are controlled by a wheel having a window 180 electrical degrees long, are shown in Figure 3-2A. The sensors and wheel must be positioned so that the output of Sensor A is in phase with the torque waveform of Phase A/B.

The sensor outputs may now be applied to logic circuitry. The logic state-
ment and waveforms for each of the six switch conditions is shown in Figure
3-2B. For example, when Sensor A is on and Sensors B and C are off (0° to 60°)
negative supply is connected to Terminal B and the positive supply is connected
to Terminal C. Referring to Figure 3-1B shows that this is the proper connec-
tion for the 0° to 60° segment.

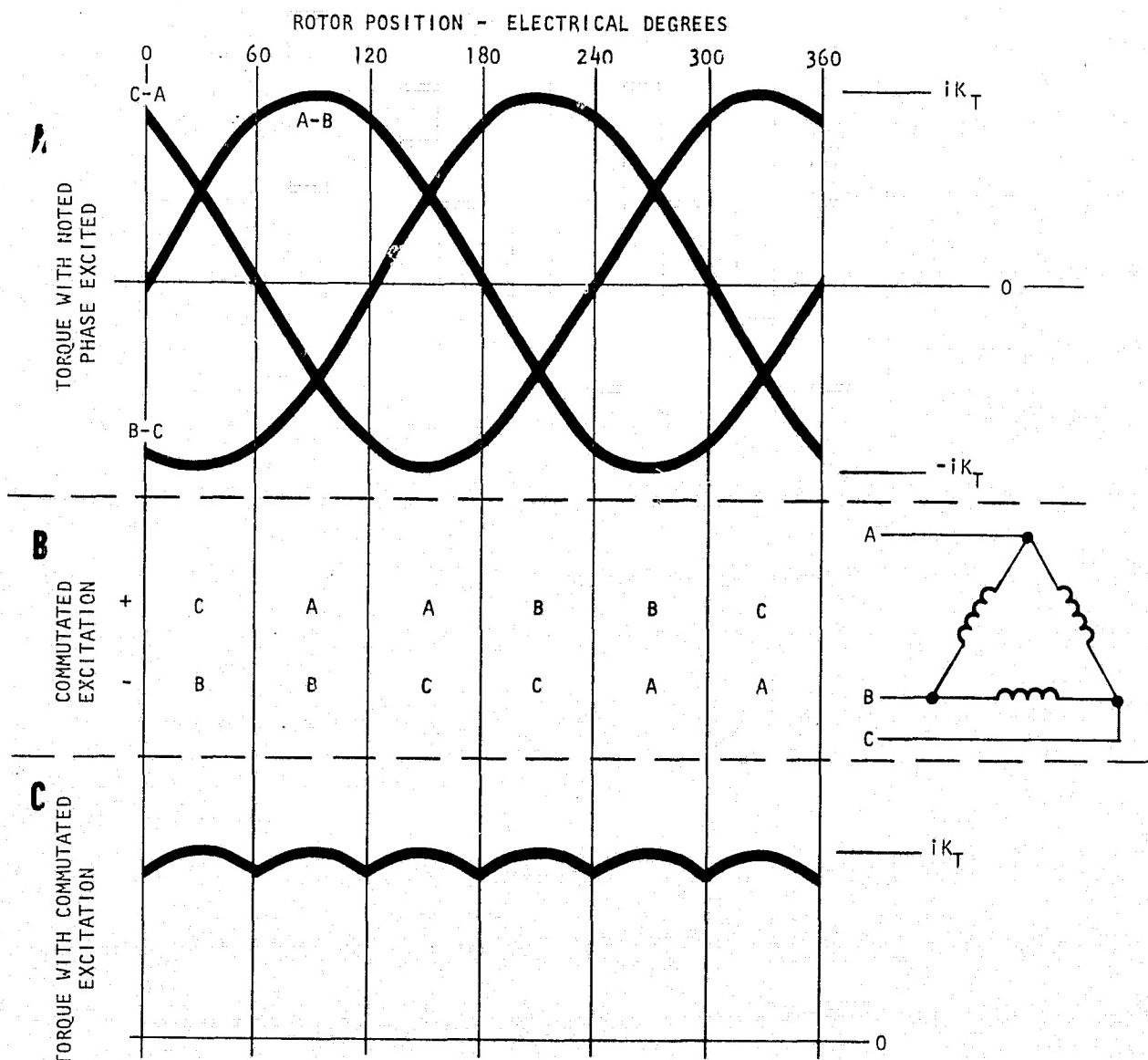
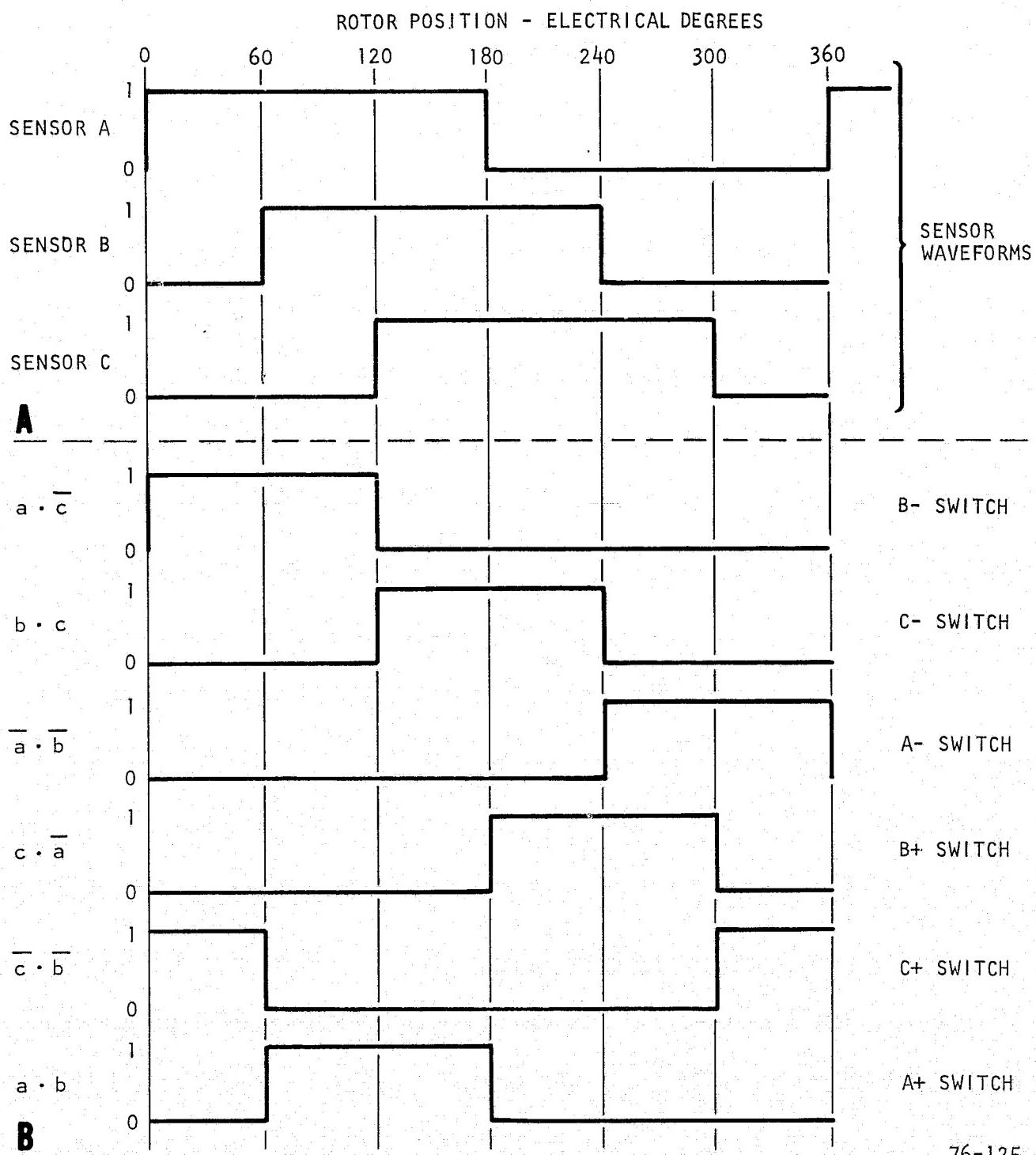


FIGURE 3-1. Commutation of a Three Phase
Delta Wound Brushless DC Motor



76-125

FIGURE 3-2. Commutation Waveforms For a Three Phase Delta Wound Brushless DC Motor

A simplified schematic that utilizes the above commutation technique is shown in Figure 3-3. Note that the sensor outputs are processed by exclusive OR gates. This feature allows the rotation to be reversed. A logic 1 on the control input inverts the sensor outputs. Referring to Figure 3-2B, note that this reverses the polarity of each motor terminal, thus making it produce torque in the opposite direction.

The motor speed, or torque can be controlled by controlling the input to the power switches, or by pulse width modulation of the input to the exclusive OR gates.

The current limit output can be used to set an absolute current limit, or it can be used to provide current feedback for constant current operation.

A two phase system can be used where circuit simplicity is a necessity and where the torque ripple can be as high as 17 percent average to peak. For instance, a velocity servo with a large angular momentum would be insensitive to the ripple torque and would be a natural for this type of system.

The output torque compared with the angle of the two phases is shown in Figure 3-4A. To simplify the drive, the motor has been wound with two centertapped phases, as shown in Figure 3-4B. The torque compared with angle graphs of the A- and B- terminals are 180° out of phase with the A+ and B+ curves which are shown.

The correct commutation sequence for producing the commutated torque graph, shown in Figure 3-4C, is obtained from Figure 3-4B.

The commutation information may be developed from the outputs of two sensors spaced 90 electrical degrees apart and looking through a window of 180 electrical degrees. The sensors and wheel must be positioned so that the Sensor A output lags the A+ torque waveform by 45 electrical degrees. The sensor outputs and the logic operations are shown in Figure 3-5.

The simplified schematic for this system is shown in Figure 3-6. As in the three phase system, a logic 1 on the control input inverts the sensor outputs and, therefore, reverses the direction of the torque output of the motor. This input may be pulse width modulated for control purposes as discussed previously.

The number of components for this system is reduced by one third as compared to the three phase system. This is the preferred system if the higher ripple torque can be tolerated, which should be the case for the claw and magazine drive requirement.

A major problem during this study has been the availability of so called off the shelf electronically commutated motors for evaluation purposes. In surveying the various manufacturers, only three (Siemens, Aeroflex, and Magnetic Technology) indicated off the shelf availability, and this means simply that a design was available, not hardware. A fourth, Curry Engineering, indicated

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

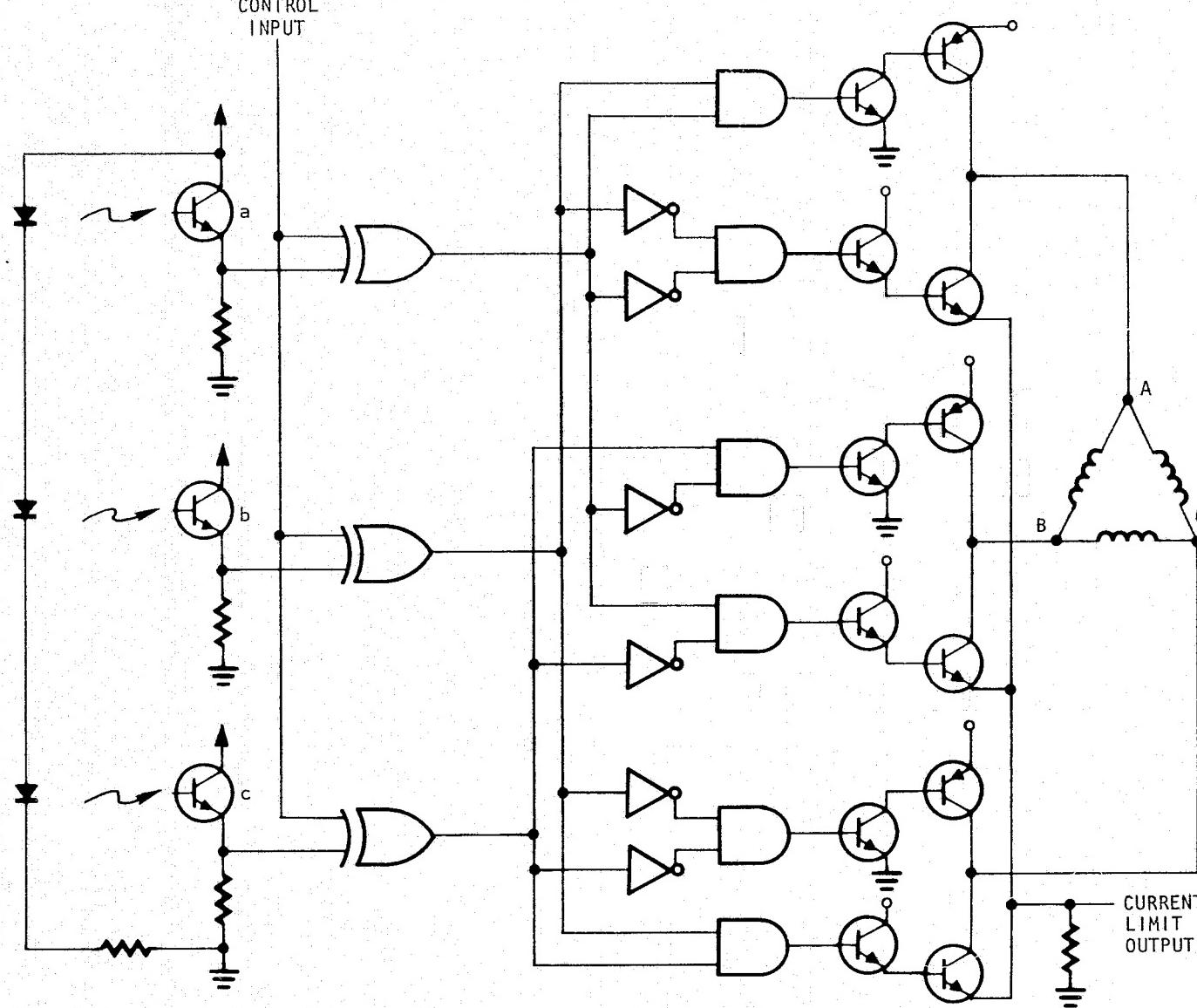


FIGURE 3-3. Simplified Schematic For Three Phase Delta Brushless DC Motor.

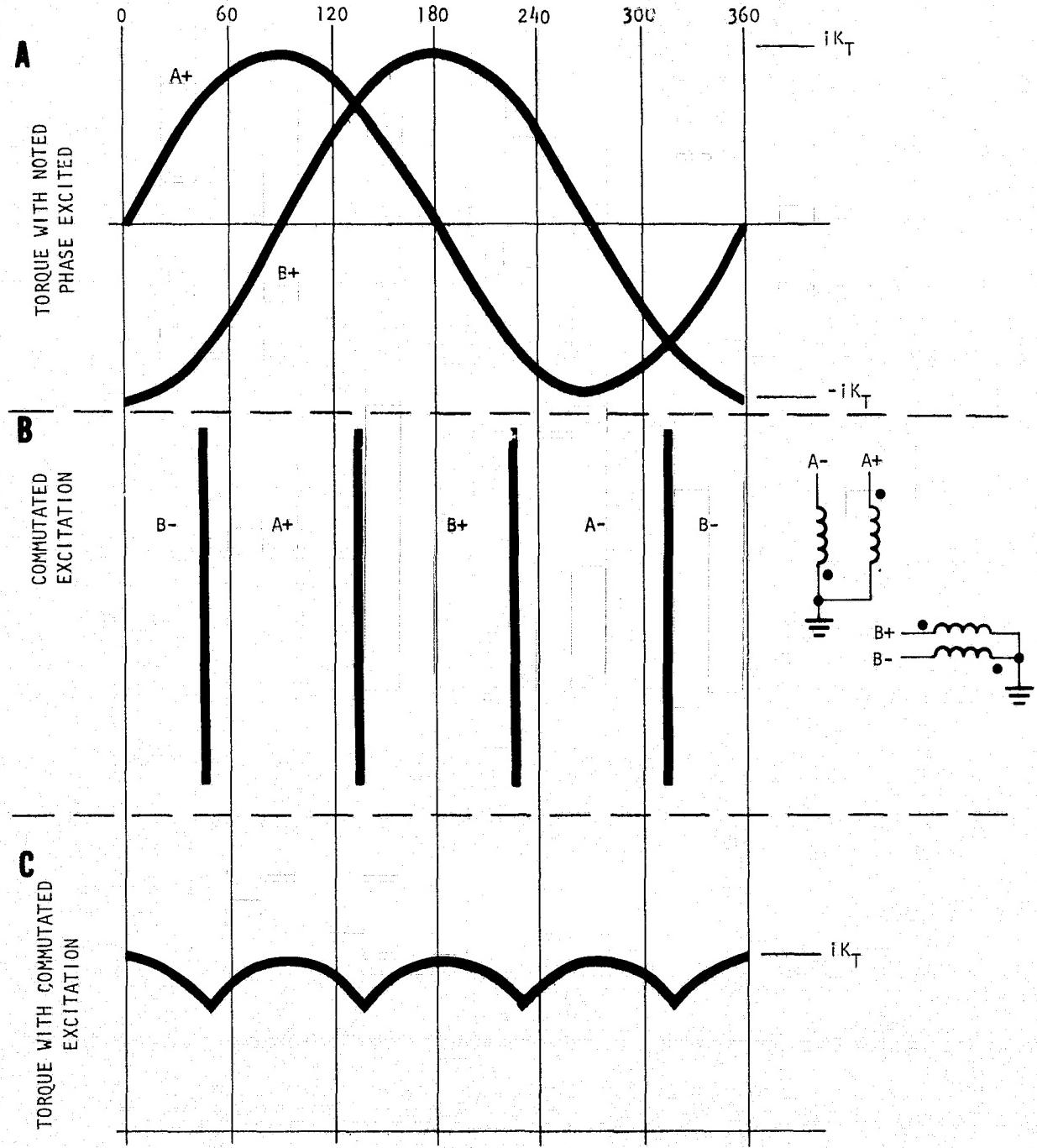


FIGURE 3-4. Commutation of a Two Phase Brushless DC Motor

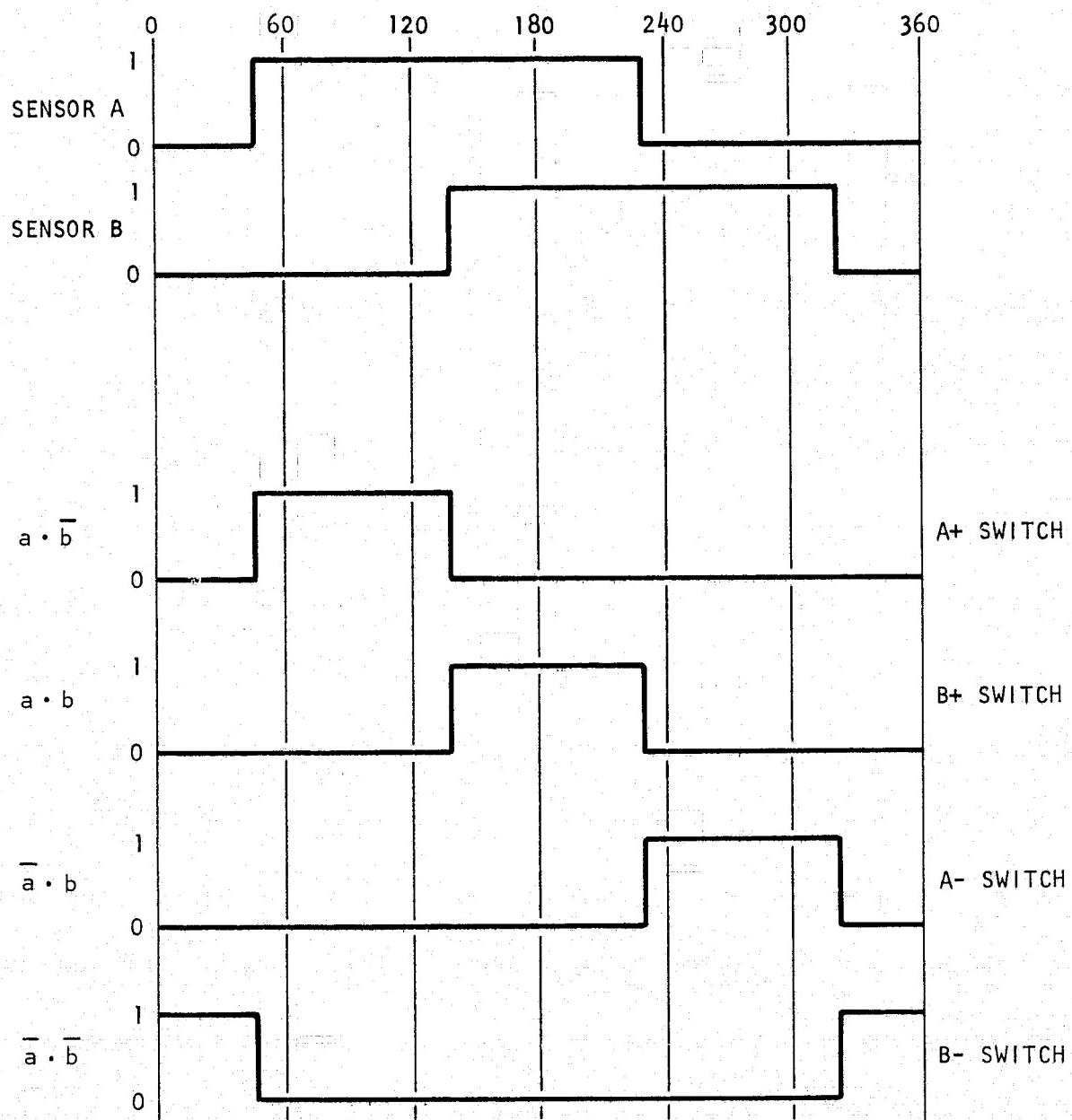


FIGURE 3-5. Commutation Waveforms For A Two Phase Brushless DC Motor

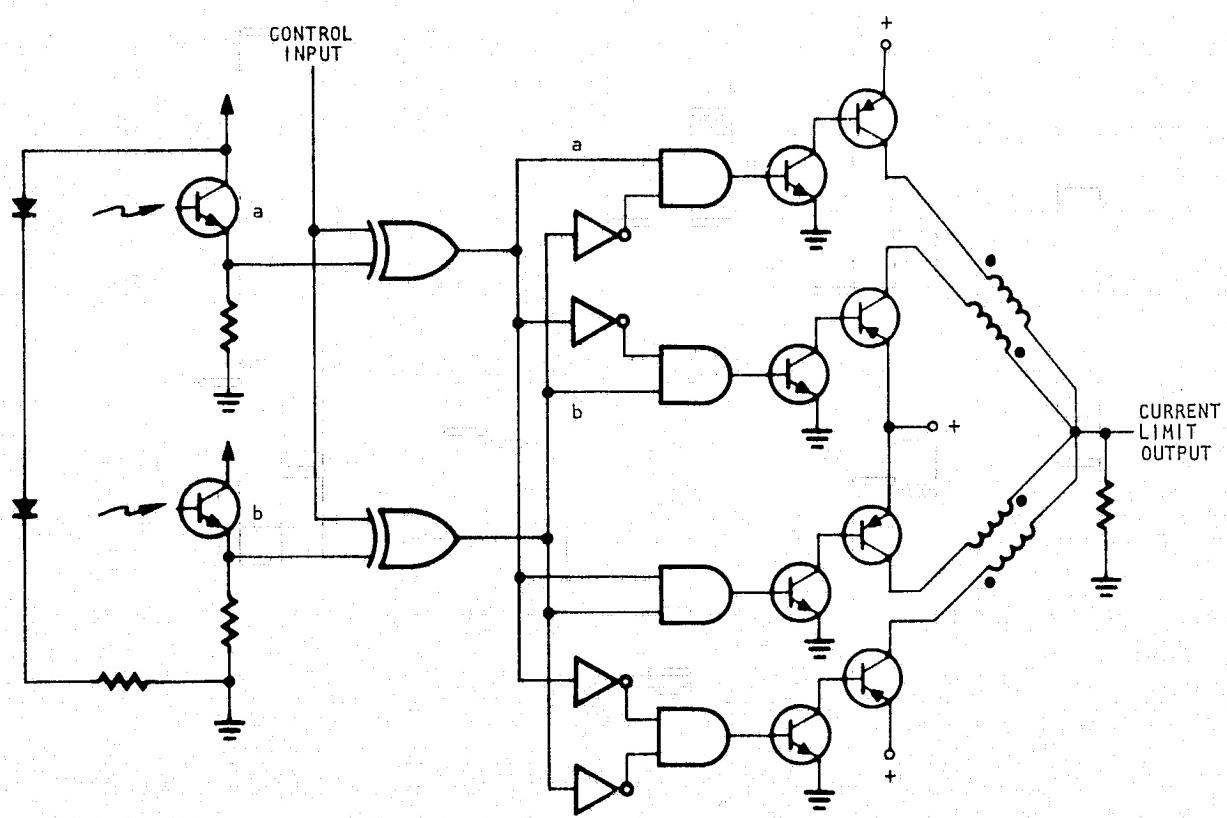


FIGURE 3-6. Simplified Schematic For
A Two Phase Brushless DC Motor

they would be interested in a special design. In pursuing this problem further, an evaluation unit has finally been obtained from Siemans. This motor, although using Hall effect devices for commutation feedback, should serve to demonstrate feasibility during breadboard testing.

Mechanical considerations are also important in the selection of drive motors. For sizes suitable for the 16 mm camera, aerospace quality motors are usually designed in standard servo component configurations. This is particularly true with stepper motors. Sizes suitable for this application are the number 8 (3/4 inch diameter) and the number 11 (1-1/16 inch diameter). The number 15 (1-7/16 inch diameter) would require a thicker camera than desired. Lengths are variable, but typical values for steppers are one inch for the number 8, 1.625 inch for the number 11, and 1.5 to 2.1 inches for the number 15. Electronically commutated dc motors are also made in standard servo sizes, and the speed control electronics can be packaged within the same cylindrical envelope. The overall lengths of these motors, not including speed control, is roughly equivalent to lengths for the brush type motors. Built-in speed control adds approximately one inch to the overall length.

Stepper motors can be supplied with either single or double shaft extensions. One or both shaft extensions can be supplied with integral pinion teeth for gear drive applications, or direct connected gear heads can be provided. The double shaft extension feature is convenient for coupling two stepper motors together when more torque is required than can be provided by a single motor. Theoretically, two motors connected in tandem can drive twice the inertial load of a single motor.

Some brushless dc motors, including the electronically commutated motor, can also be supplied in a pancake version where the diameter is large in relation to the length. This configuration could be an advantage for the magazine drive function because the motor could possibly be fitted into the camera with the shaft parallel to the spline drive for the magazine, eliminating the need for right angle gearing. However, because mass moment of inertia is proportional to the fourth power of diameter, motors with large diameter rotors are not generally well suited for applications where fast starting and stopping are required. Pancake configuration motors are generally supplied without end bells, bearings, and shaft. These are supplied by the user to best meet the configuration requirements.

Because of the variety of sizes and shapes available in stepper motors and electronically commutated dc motors, a serious problem is not anticipated in the packaging of the new camera drive in a configuration compatible with the size requirements of a 16 mm space sequential camera.

4. SYSTEM APPROACHES

The different types of dc brushless motors, the various electronic control techniques for these motors, and the options for various groupings of camera functions under one or two motors make possible a number of different approaches and subapproaches for meeting the requirements of the study. Although most of these approaches were anticipated at the time of the proposal, new possibilities were brought to light during the investigation of each approach during the study. The more promising approaches that were studied, and the paths that were taken in arriving at the approaches which presently appear the best for the breadboard are shown in Figure 4-1. The following discussion covers the investigations of these approaches and the line of reasoning which leads to the present conclusions.

4.1 SINGLE MOTOR DRIVE SYSTEM

If all other considerations were equal, the obvious choice would be the use of a single motor drive. However, the restriction against a clutch makes the use of a single motor difficult. In considering the use of a single motor, understanding the function of the clutch in the conventional camera system is necessary. This device provides the capability of starting, stopping, and running in a pulse mode without having to accelerate or decelerate the drive motor and without concern for the position of the motor shaft at any particular time. Elimination of the clutch must take into account two important requirements; pulse mode operation, and constant exposure independent of frame rate.

From the standpoint of power and speed, the electronically commutated dc motor would be a wise choice for the single motor approach, but its characteristics are essentially the same as the brush type dc motor, making a clutch necessary if the camera will be operated like the DAC. However, by running cine mode for 24, 12 and 6 fps, pulse mode for 2 fps, and compensating for a one stop shift slower in exposure time at 12 fps and two stops at 6 fps with the AEC, eliminating the clutch might be possible.

A stepper motor could be used, but it would probably be impossible to simultaneously meet both the torque and the stepping rate requirements with a motor meeting the size requirements, without resorting to a method for reducing the acceleration and deceleration requirements. Such a method was discussed in the proposal, and has been given further study in Phase I of the contract. A description of the method, taken from the proposal, is included in Appendix B of this report for reference. The following analysis evaluates the method, with several variations, for application to the single motor drive. The key

NUMBER OF MOTORS



A

1 MOTOR

2 MOTORS

DIVISION OF LOADS

B

SHUTTER
CLAW/ MAGAZINE

SHUTTER/CLAW
MAGAZINE

MOTOR TYPES

C

STEPPER

STEPPER

ELECTRONIC
COMMUTATED DC

OPERATING PRINCIPLES

CONVENTIONAL
2 PIECE
SHUTTER

1 PIECE
SHUTTER

EXTERNAL
DRIVE

INTERNAL
FEEDBACK
(HIGH FRAME
RATES)

(LOW FRAME
RATES
AND PULSE MODE)

D

MULTISTEP

2 STEP

FIGURE 4-1. Development of Approaches

is bringing the motor and its load up to speed with two or more progressively higher stepping rates, rather than in one jump. However, because of the need to precisely position the shutter in relation to the pull down cycle, only certain combinations of step rates and numbers of steps will work. These combinations are determined from the following equations,

$$N_1 + N_2 + N_3 + \dots + N_n = \frac{360}{\theta} \quad (1)$$

$$\frac{N_1}{C_1} + \frac{N_2}{C_2} + \frac{N_3}{C_3} + \dots + \frac{N_n}{C_n} = \frac{1}{F}, \quad (2)$$

where N = Number of steps at each step rate

C = Step rate, steps/second (SPS)

F = Frames per second (fps)

θ = step angle

Using these equations, it can be shown that the following combinations will work for a 15° stepper motor, that is, each combination will produce 360° of rotation in a time which is an even multiple of $1/24$ second. The identifying numbers on the left are the same as used in the proposal, except for 5 and 6 which were added later.

- (1) All steps at 576 SPS
- (2) 12 steps at 192 SPS/12 steps at 576 SPS
- (3) 6 steps at 144 SPS/6 steps at 288 SPS/12 steps at 576 SPS
- (4) 6 steps at 72 SPS/6 steps at 144 SPS/12 steps at 288 SPS/24 steps at 576 SPS
- (5) 4 steps at 96 SPS/8 steps at 384 SPS/12 steps at 576 SPS
- (6) 6 steps at 120 SPS/6 steps at 480 SPS/12 steps at 576 SPS

These combinations are plotted in Figure 4-2, in terms of angular rotation versus time, with each continuous line representing one combination, and with the slope of each line segment representing the step rate (and motor speed).

In order for the scheme to work, the motor must be able to make the transition between two successive step rates (changes in slope on Figure 4-2) without losing a step. The torque required will be:

$$T = J\alpha + T_F \quad (3)$$

where, T = total torque

J = mass moment of inertia

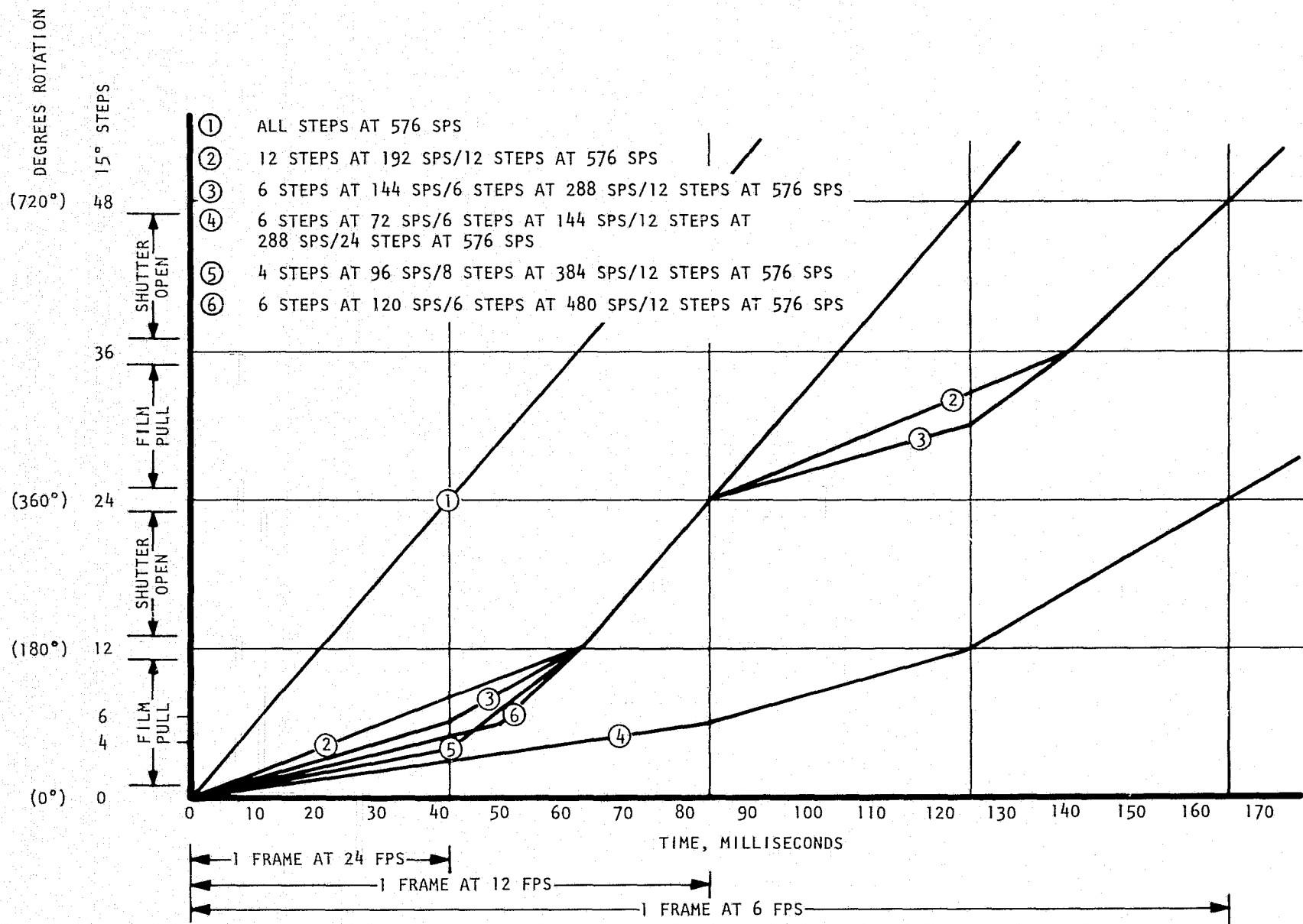


FIGURE 4-2. Shutter and Claw Motion Compared With Time For Various Combinations of Steps and Stepping Rates for a 15° Stepper Motor Camera Drive

α = angular acceleration, radians/second²

T_F = torque due to friction

In order not to lose a step, the acceleration should not be less than the change in angular velocity divided by the period of one step at the higher velocity, or:

$$\alpha = \frac{\omega_n - \omega_{n-1}}{\frac{1}{C_n}} \quad (4)$$

Where the subscripts n-1 and n refer to conditions before and after the change in step rates.

The angular velocity is given by the expression:

$$\omega = \frac{\pi}{180} \theta C \text{ radians/second} \quad (5)$$

Using (5) in (4):

$$\alpha = \frac{\pi}{180} \theta C_n (C_n - C_{n-1}) \text{ radians/sec}^2 \quad (6)$$

and using (6) in (3):

$$T = \frac{\pi}{180} \theta C_n (C_n - C_{n-1}) J + T_F \quad (7)$$

Now, the torques required for each stepping rate transition, using a 15° stepper, are computed using the loads shown in figure 2-2. For units of oz in (units used by motor manufacturers), equation (7) becomes:

$$\begin{aligned} T &= \frac{\pi 15}{180} C_n (C_n - C_{n-1}) 2.83 \times 1.42 \times 10^{-5} + T_F \\ &= 1.05 \times 10^{-5} C_n (C_n - C_{n-1}) + T_F \text{ oz in,} \end{aligned} \quad (8)$$

where $T_F = 1.24$ oz in max while the claw is pulling film, and 0.318 oz in max while the film is stationary in the aperture.

The smaller figure represents the torque that causes the take-up clutch in the magazine to slip near the end of film transport (worst case), reflected back to the motor shaft. This value cannot be exceeded, regardless of the acceleration of the drive, because this is the maximum torque that the clutch will transmit.

Table 4-1 gives the results for torque requirements, using equation (8), for the allowable combination of steps and stepping rates shown in Figure 4-2.

These values are also plotted in Figure 4-3 with the numbers adjacent to each point identifying the combinations of steps and stepping rates used in the analysis. Also plotted in Figure 4-3 are speed/torque characteristics for size 8, 11, and 15 variable reluctance 15° stepping motors, using data from the catalog of the Computer Components Corporation of California. Interpreting Figure 4-3, each motor should be able to handle any condition to the left of its characteristic curve. For example, for the number 8 motor to handle combination number 5, all points labeled 5 should fall to the left of the number 8 motor curve.

Note that the best combination of steps and stepping rates in terms of minimum torque requirements are the ones where the points fall as far to the left as possible. Although all combinations have points falling near the origin, they also have at least one more point falling considerably to the right. Examination shows that combination 5 has the lowest maximum torque requirements and that the two highest values are nicely matched to the slopes of the number 11 and number 15 motor curves. Thus, on this basis alone, combination 5 would be the logical choice.

The characteristic curves show that combination 5 can be handled by the number 15 motor, and because of the approximate nature of the analysis, it could also possibly be handled by the number 11. Unfortunately, the number 15 frame size (1-7/16 inch diameter), is not compatible with the goal of minimum camera envelope.

This same type of analysis is applied later in the report to separate stepper motors driving a shutter, and a claw. Breadboard tests have shown the results are conservative as far as the inertial loads are concerned, that is, that the motors can actually drive greater inertial loads than analysis would indicate. Analysis and component testing thus substantiates the feasibility of a single stepper drive for a 16 mm space sequential camera of the DAC type. However, the control scheme would be complicated compared with other approaches, and the motor larger than desired.

The discussion so far assumes use of a stepper motor for a single motor approach, because this type offers the best speed of response together with accurate positioning, both necessary if the clutch is to be eliminated and all of the requirements listed in Section 2 must be met. However, if requirement 4 (independent shutter speeds and frame rates) is taken away, the electronically commutated dc motor can also be used.

Tests with this type motor in the breadboard driving the claw and magazine were impressive. Good speed control was obtained at 24, 12 and 6 fps. At 2 fps, and in the pulse mode, it was found that the motor could be easily pulsed one frame at a time, without elaborate circuitry. Since the shutter load would add very little to the power requirements for the motor, this suggests that the single motor approach with the electronically commutated motor is a very practical and straightforward one, again if requirement 4 is removed.

TABLE 4-1. Total Camera System Torque Requirements
For Stepping Rate Transitions

| Combination (See Fig 4-2) | 1st Increment | | | | 2nd Increment | | | | 3rd Increment | | | | 4th Increment | | | |
|------------------------------|---------------|-------|-------|-------|---------------|-------|-------|-------|---------------|-------|-------|-------|---------------|--|--|--|
| | C_0 | Steps | C_1 | T_1 | Steps | C_2 | T_2 | Steps | C_3 | T_3 | Steps | C_4 | T_4 | | | |
| 2 | 0 | 12 | 192 | 0.705 | 12 | 576 | 2.64 | | | | | | | | | |
| 3 | 0 | 6 | 144 | 0.536 | 6 | 288 | 1.675 | 12 | 576 | 2.06 | | | | | | |
| 5 | 0 | 4 | 96 | 0.415 | 8 | 384 | 2.40 | 12 | 576 | 1.48 | | | | | | |
| 6 | 0 | 6 | 120 | 0.469 | 6 | 480 | 3.05 | 12 | 576 | 0.899 | | | | | | |
| 4 | 0 | 6 | 72 | 0.372 | 6 | 144 | 1.349 | 12 | 288 | 0.753 | 24 | 576 | 2.06 | | | |

C = Step rate (SPS)

T = Torque to make transitions (oz in)

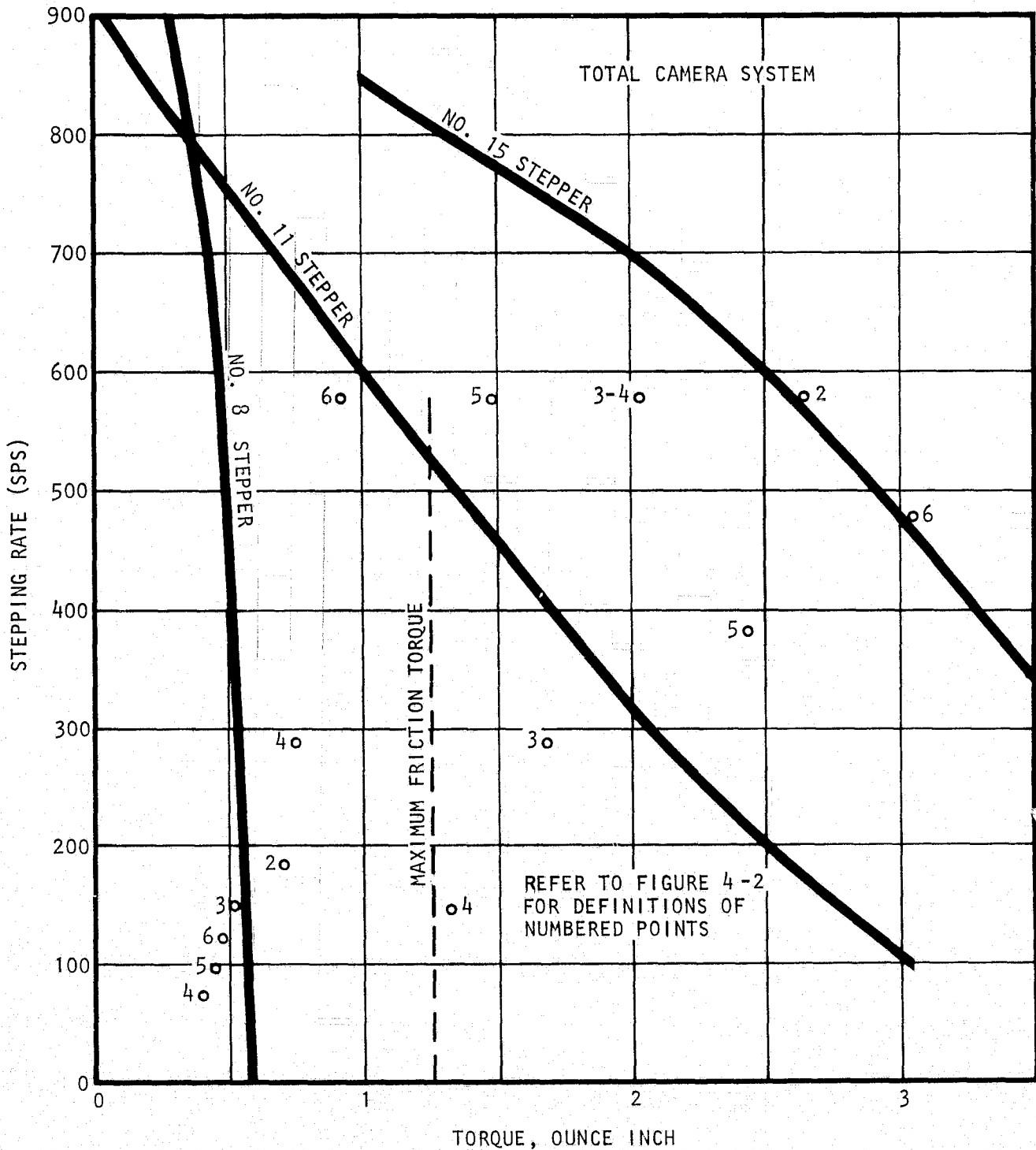


FIGURE 4-3. Transition Torque Requirements from Table 4-1
Compared With Stepper Motor Characteristics

With automatic exposure control, this relaxation in requirements would not be serious, because the slower shutter speeds associated with lower frame rates could be easily compensated for by the AEC, through either the variable width shutter or the lens iris.

4.2 TWO MOTOR DRIVE APPROACHES

There are some very practical advantages to dividing the total load between two motors, if one or both are steppers. The two most logical divisions of load for a two-motor system are shown in Figure 4-1B. The major advantage to the one on the right, grouping the shutter and claw under one motor, and magazine drive requirements under the other are purely mechanical. The shutter and claw are close together at the front of the camera, while the film sprockets and film take-up are in the magazine. Thus, this division of loads would eliminate the gear train presently joining these functions in the DAC.

An examination of functions shows the alternative on the left to have other very natural advantages. The camera shutter is the device requiring the most accurate speed control, and has no appreciable friction loads imposed on it. Further, it can be designed with relatively low inertia. The claw and magazine on the other hand, involve considerable mechanism, and include almost all of the frictional loads in the camera. Thus, it would make sense to drive the shutter with a small, highly responsive and positionally accurate motor, and the remainder of the camera with a higher torque but less responsive device. Further investigation of this approach revealed other attractive possibilities. For instance, by separating the shutter from all other mechanisms, eliminating the relatively complex mechanism and the electronics involved in varying the shutter opening for AEC might be possible. This will be discussed in more detail later. Since positional control of the remaining mechanism is not nearly so critical as the shutter, these functions could be driven by an electronically commutated dc motor, offering the desirable characteristics of an ordinary dc motor, without the brushes. In view of these possibilities for establishing major breakthroughs in camera system design, this latter division of loads was selected for further study.

As shown in Figure 4-1D, the choice is between the conventional two piece rotating (pie section) shutter used in the DAC, or a one piece shutter design. Reviewing briefly, the DAC design uses two rotating shutter blades with 135° openings each. The actual (combined) opening at any time is determined by the relative positions of the two blades, which rotate in the same direction. One shutter blade is driven directly, the other through a spur gear differential mechanism, which can be adjusted during running, or when stationary to vary relative angular positions of the blades, and thus the shutter opening.

For AEC, this variation is achieved by driving a separate stepper motor which, through the differential, varies the shutter opening in 1/4 f stop increments. Since the relationship between opening and f stop is logarithmic, special cams or noncircular gears are required between the AEC stepper and differential. Also, an encoder is required on the stepper drive to read and store the value of the shutter opening, for use by the electronic control system. The general arrangement is shown in Figure 4-4.

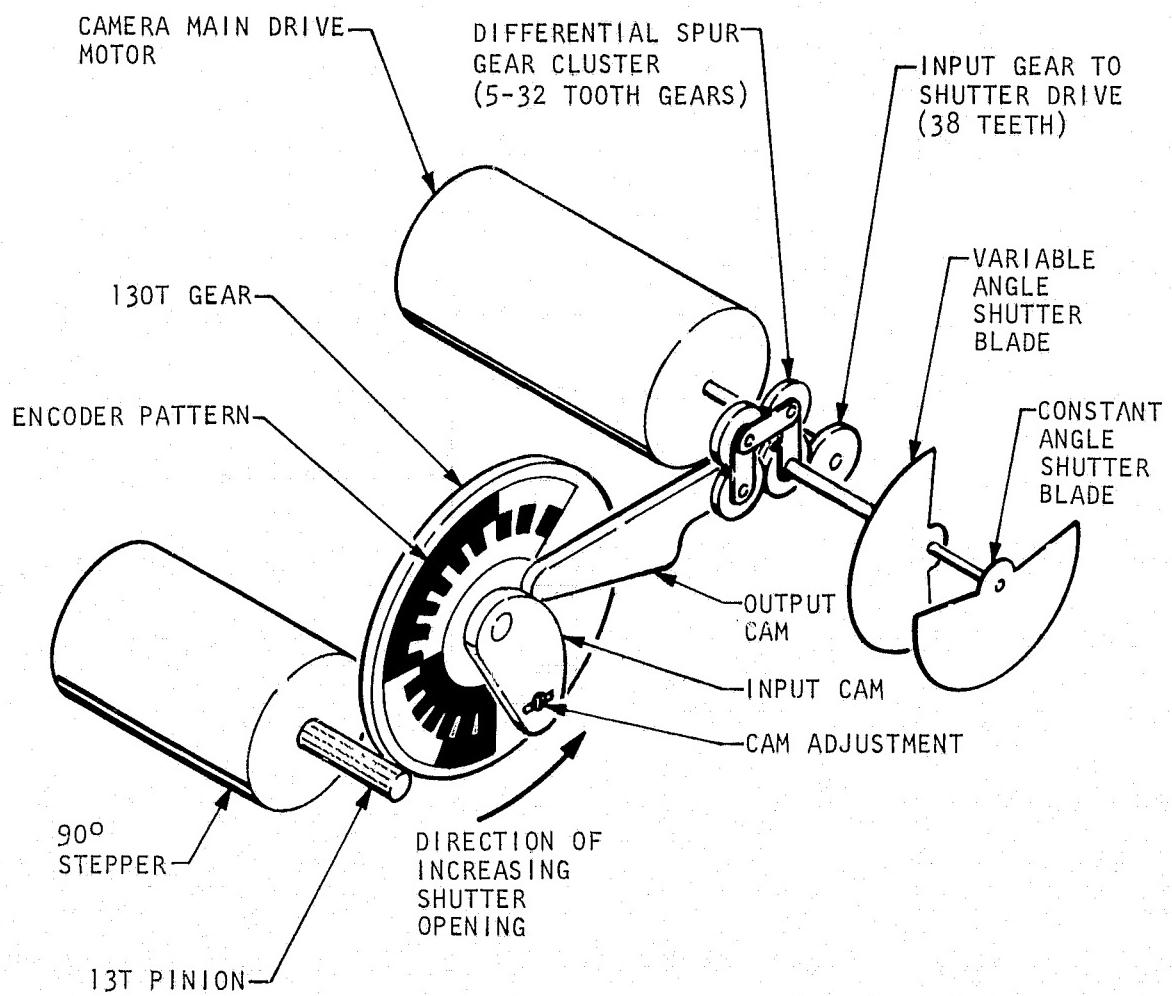


FIGURE 4-4. Shutter Control With AEC, Mechanical Subsystem

In order to test the capability of a stepper motor to drive this mechanism in the manner required by the present camera system, a dummy shutter of approximately the same mass moment of inertia was attached to a number 8, 15° stepper motor. An electronic control circuit was breadboarded to drive this motor in combinations 2, 3, and 4 discussed earlier under the single motor drive, and also a combination described in the proposal as method 1, where the motor goes directly from 0 to 576 steps per second. Except for instability tendencies in combination 2, the system performed well for combinations 2, 3, and 4. (Combination 1 was out of the question, as expected.) The instability appeared to be related to slowing down rather than accelerating the load. Light friction damping relieved this tendency.

A subsequent analysis was performed along the lines discussed for the one motor approach. The results, shown in Table 4-2 and Figure 4-5, show either that the system should not work, or that the method of analysis is overly pessimistic. Reexamination of the analysis indicates that the premise used, namely that the motor must accelerate to a new pulse rate during the first pulse at the higher rate, is too severe an assumption. Thus, it appears that the motor may take slightly longer to make each transition, but is still fast enough not to miss a step. If it is assumed that the motor can make the transition in the period of two pulses rather than one, then combinations 3 and 4 would fall within the allowable speed/torque envelope, and combination 2 would come close. Although this discussion points out the approximate nature of the analysis, it is sufficiently conservative to avoid making serious errors in judgement based on the results.

These tests and analysis clearly demonstrate the feasibility of driving the conventional two piece shutter with a single number 8 stepper motor. However, the very attractive possibility of eliminating the complicated mechanism associated with this design led to investigations of a one piece shutter design offering the utmost in mechanical simplicity.

4.2.2 SINGLE BLADE SHUTTER

With the shutter drive isolated from the rest of the camera mechanism, the possibility arises that variable exposure times can be achieved by varying the shutter speed only, obviating the need for variable shutter openings. For such a scheme to work, the shutter opening must move across the aperture at a precisely controlled speed, stopping at a predetermined position. The next exposure could then be made by rotating the shutter in the opposite direction. Since the shutter would be extremely simple, reducing the inertia to the point where such a scheme would be feasible using a number 8 stepper motor might be possible. The following section describes two possible methods for mechanizing this approach.

4.2.2.1 Multistep Approach

The concept here is that the stepper motor can be made to drive a one piece shutter with fixed opening over a range of speeds sufficient to cover exposure times from 1/62.5 to 1/1000 of a second. For this analysis, a 15° stepper is used, moving through eight steps to expose one frame of film. The maximum

TABLE 4-2. Two Piece Shutter Torque Requirements
For Stepping Rate Transitions

| Combination (See Fig 4-2) | 1st Increment | | | | 2nd Increment | | | | 3rd Increment | | | | 4th Increment | | | |
|------------------------------|---------------|-------|-------|-------|---------------|-------|-------|-------|---------------|-------|-------|-------|---------------|--|--|--|
| | C_0 | Steps | C_1 | T_1 | Steps | C_2 | T_2 | Steps | C_3 | T_3 | Steps | C_4 | T_4 | | | |
| 2 | 0 | 12 | 192 | 0.195 | 12 | 576 | 1.17 | | | | | | | | | |
| 3 | 0 | 6 | 144 | 0.110 | 6 | 288 | 0.220 | 12 | 576 | 0.879 | | | | | | |
| 4 | 0 | 6 | 72 | 0.027 | 6 | 144 | 0.055 | 12 | 288 | 0.220 | 24 | 576 | 0.879 | | | |

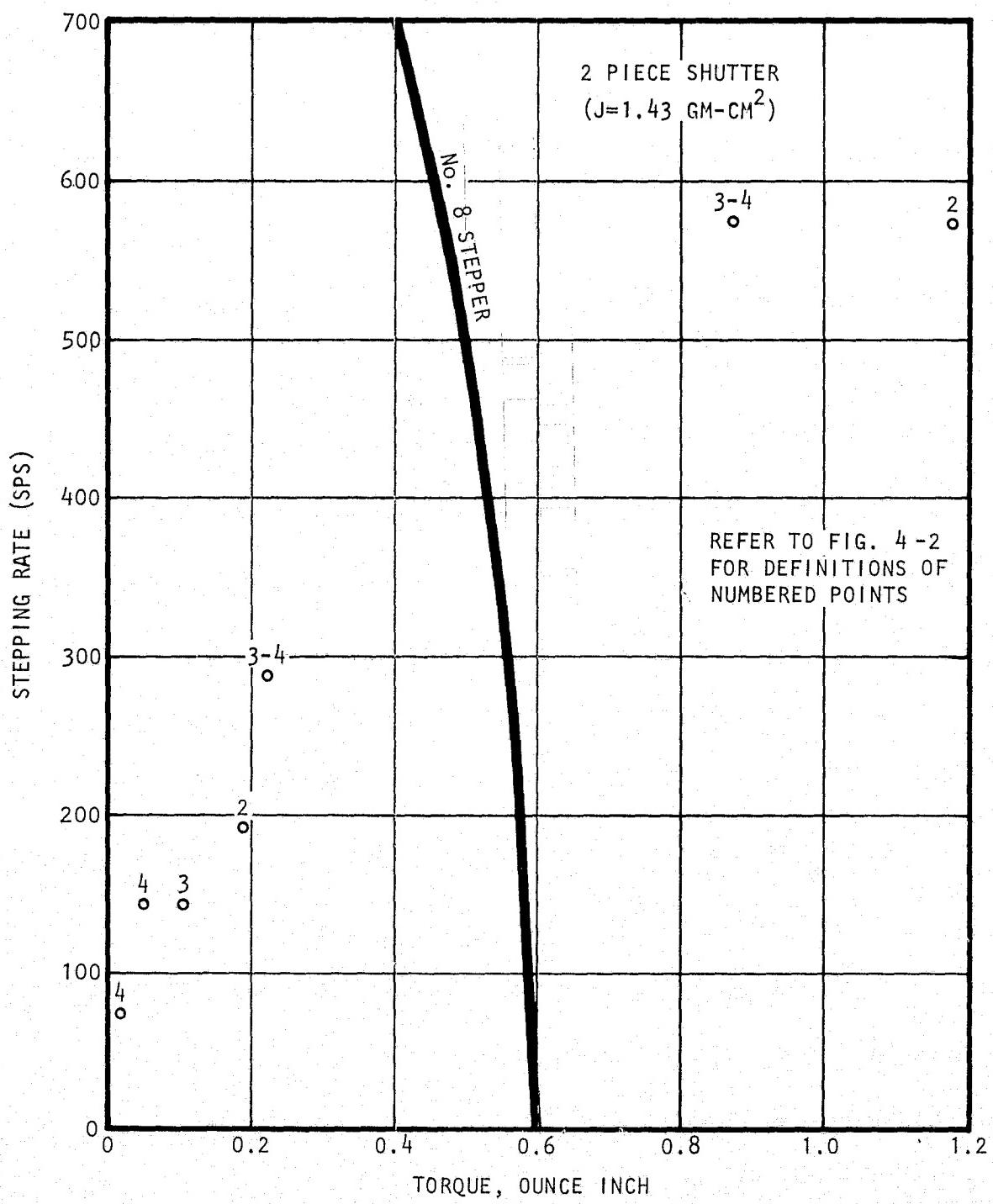


FIGURE 4-5. Transition Torque Requirements From Table 4-2
Compared With Stepper Motor Characteristic

time that can be allowed per frame will be $1/24$ fps = 0.0416 second. Thus, the minimum pulse rate will be $24 \times 8 = 192$ pulses per second.

For the maximum exposure time ($1/62.5$ second), the shutter opening angle will be:

$$A = 15^\circ \times 192 \times \frac{1}{62.5} = 46.1^\circ$$

Shorter exposure times will be achieved by going to higher pulse rates. Table 4-3 shows how the shutter exposure times, in $1/4$ f stop increments, can be achieved by increasing the pulse rate. Unfortunately, the full range of exposures cannot be realized in this manner, because stepping rates would be too high. However, this problem can be avoided by adding two smaller shutter openings, for a total of three, 120° apart from each other. Thus, in Table 4-3, after reaching an exposure time of 0.00673 second (with a pulse rate of 456 pulses per second), the shutter is rotated 120° to a new opening of 16.3° , giving an exposure time of 0.00566 second with a pulse rate of 192 pulses per second. Still faster exposure times are then achieved by going through the same sequence of pulse rates as before, until an exposure time of 0.00238 seconds is reached. Then the shutter shifts another 120° to a 5.76° opening, and the sequence of pulse rates is again repeated until $1/1000$ second is achieved at 384 pulses per second.

The fixed opening shutter used in this discussion is shown in Figure 4-6. The feasibility of this approach was tested using a number 8 motor and a 0.007 inch mylar shutter blade for minimum inertia. The motor was able to achieve the necessary reversals in rotation at up to 576 pulses per second, but there are apparently four rather serious limitations to this approach. These limitations are:

1. The shutter must be extremely light weight to have the necessary low inertia, but this is not considered an insurmountable problem.
2. Four clocks would be needed to generate the motor drive pulses, instead of one) two of the six pulse rates are generated as multiples or submultiples of the others).
3. This particular design offers a margin of only 5.5° overlap of the shutter to the aperture with the largest opening (46.1°).
4. The most serious problem is the possibility of banding on the developed film due to small variations in shutter speed, particularly at low pulse rates, as the opening progresses across the aperture.

An alternate scheme was devised, using two openings instead of three, of 46.1° and 11.5° . For a shutter travel of 120° , the maximum pulse rate would be 768 Hz, and the overlap margin between the shutter and aperture would still be 5.5° . But now, because there would be only two openings, the travel could be increased to a maximum of 180° with corresponding improvement in the shutter/aperture overlap, but with associated increases in maximum pulse rate.

TABLE 4-3. Relation of Exposure Time to Step Rate
And Shutter Angle For One Piece, Three Opening Shutter
Direct Connected to 15° Stepper Motor

| t_e | 46° Angle | 16° Angle | 5.8° Angle |
|---------|-------------------|-------------------|-------------------|
| | Step Rate (Hz) | Step Rate (Hz) | Step Rate (Hz) |
| 1/62.5 | 192 | | |
| 0.0135 | 228 | | |
| 0.0113 | 272 | | |
| 0.00951 | 323 | | |
| 1/125 | 384 | | |
| 0.00673 | 456 | | |
| 0.00566 | | 192 | |
| 0.00476 | | 228 | |
| 1/250 | | 272 | |
| 0.00336 | | 323 | |
| 0.00283 | | 384 | |
| 0.00238 | | 456 | |
| 1/500 | | | 192 |
| 0.00168 | | | 228 |
| 0.00141 | | | 272 |
| 0.00119 | | | 323 |
| 1/1000 | | | 384 |

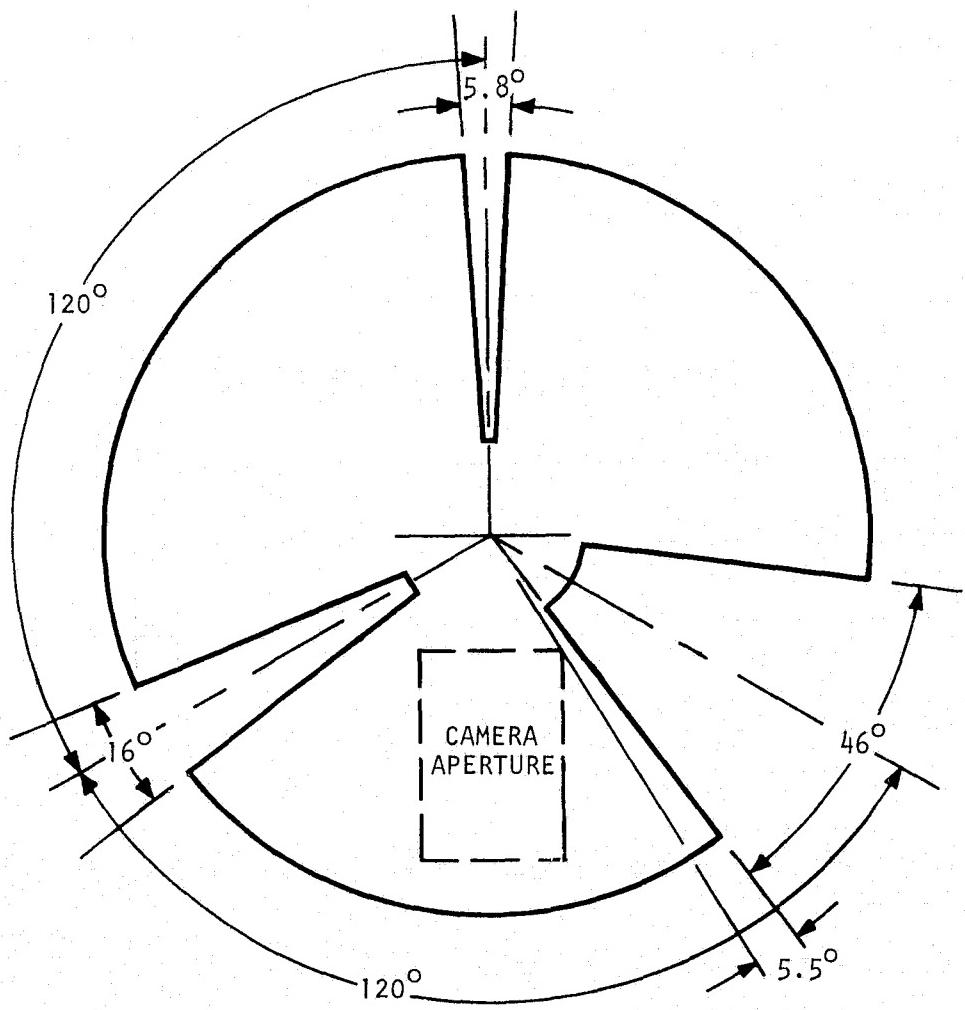


FIGURE 4-6. One Piece, Three Opening Shutter
For 15° Stepper Motor

These relations are shown in Table 4-4 including overlap in decimals of an inch, which is more meaningful than in degrees. Note that as the overlap becomes more favorable, the maximum stepping rate gets up to values which would be difficult or impossible to achieve with the number 8 motor. Also, the possible problem of banding is still present, and unless the shutter travel is 180° , the electronics get more involved than for the three opening shutter. Therefore, the two opening approach apparently offers little, if any advantage over the three opening approach.

Although both these approaches appear feasible, the next approach discussed is selected as being more promising.

4.2.2.2 One Piece Shutter, Two Step Approach

One approach for eliminating the banding problem would be to perform one exposure frame in two steps, the first step to open the shutter and the second step to close it. The following frame would be exposed in the same manner, but with reverse rotation. Exposure time would be controlled by the dwell time between the two steps involved in each exposure.

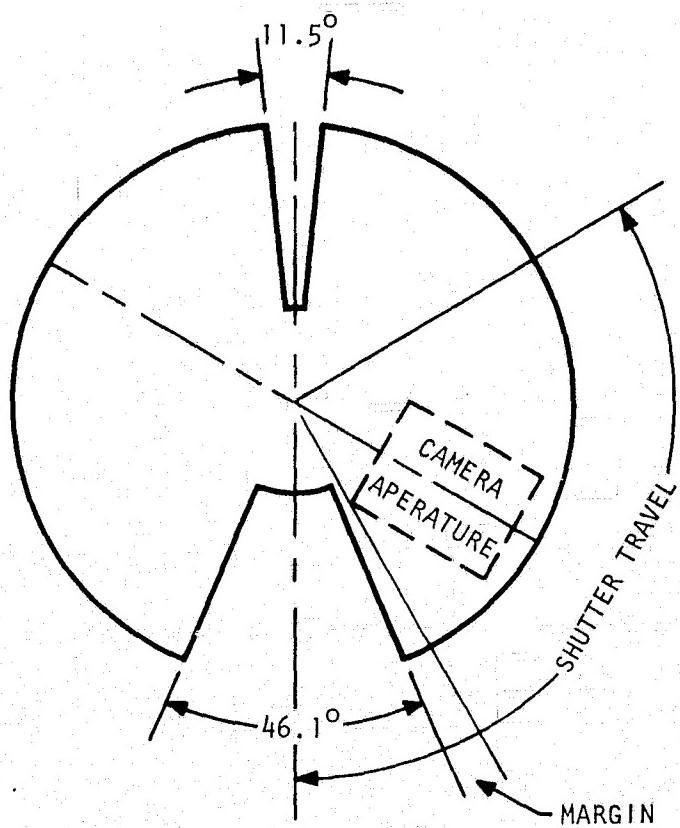
A number 8, 45° stepper was selected for this analysis. Ideally, the shutter would be attached directly to the motor shaft, but if this is not practical because of motor frame interference with the optical path through the camera aperture, a pair of gears, segments of gears, or other mechanisms, could be used between the motor and the shutter. This approach is shown in Figure 4-7, for gear ratio of 1.6 to 1, giving a shutter travel of 72° per step, or 144° total travel. The travel of the shutter can be varied by changing the gear ratio, which in turn varies the distance between the center of the shutter and the aperture. Also, varying the gear ratio has a large affect on the mass moment of inertia on the shutter, which will be a critical consideration in the design. Varying the gear ratio affects the inertia of the shutter for three reasons; it affects the geometry (shape), it affects the diameter of the shutter circle, and it affects the overall inertia reflected back to the motor shaft by the factor of the square of the gear ratio. The relative shutter inertia and shutter travel angle as functions of shutter circle diameter are shown in Figure 4-8. An advantageous situation occurs where the total angle of travel is 90° , because in this case attaching the shutter directly to the motor shaft might be possible, eliminating the gears which would add about 10% to the shutter inertia.

In the event that greater separation is required between the shutter shaft axis and the aperture, the motor can be moved further from the aperture and still retain the direct drive, but at the cost of a larger shutter. Both the minimum inertia shutter used in the analysis for Figure 4-8, and a larger shutter which could be driven directly from the motor are shown in Figure 4-9. The inertia for the larger shutter is also shown in Figure 4-8, for comparison.

This approach to the one piece shutter could eliminate all of the limitations listed in Paragraph 4.2.2.1 for the multistep one piece shutter, except for the requirement for a very light weight shutter design. This problem will be solved by finding the best combination of material and configuration.

TABLE 4-4. Relation of Maximum Stepping Rate
And Shutter/Aperture Margin to Shutter Travel,
For One Piece, Two Opening Shutter
on a 15° Stepper Motor

| Shutter Travel | | Max Step Rate | Shutter/Aperture Margin | |
|----------------------|-------------|---------------|-------------------------|-------------------------|
| Steps (15°) | Angle | SPS | Degrees | Minimum Distance (inch) |
| 8 | 120° | 768 | 5.5 | 0.028 |
| 9 | 135° | 864 | 10.1 | 0.052 |
| 10 | 150° | 960 | 14.7 | 0.076 |
| 11 | 165° | 1056 | 19.3 | 0.097 |
| 12 | 180° | 1152 | 23.9 | 0.120 |



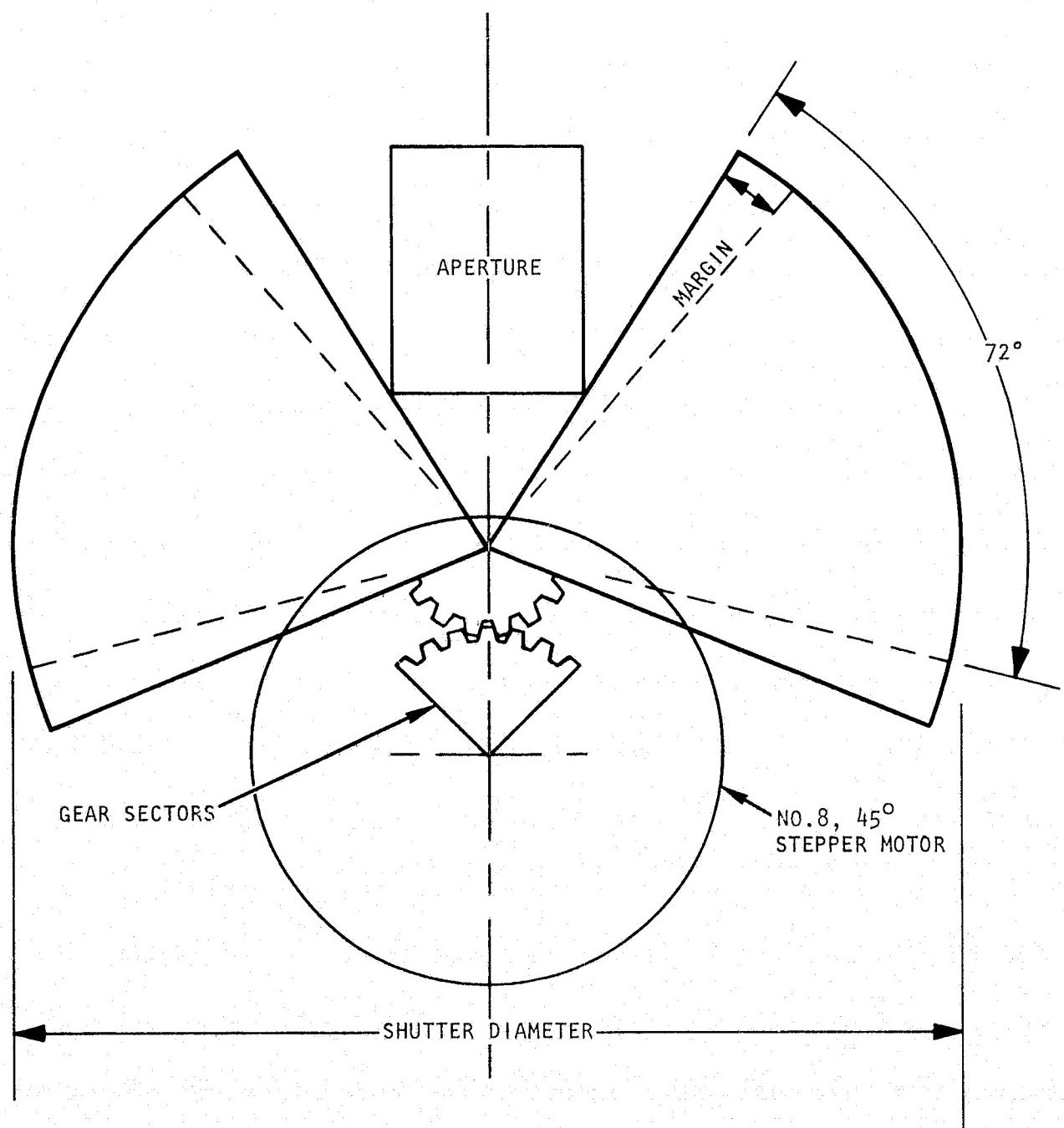


FIGURE 4-7. One Piece Shutter, Two Step Approach

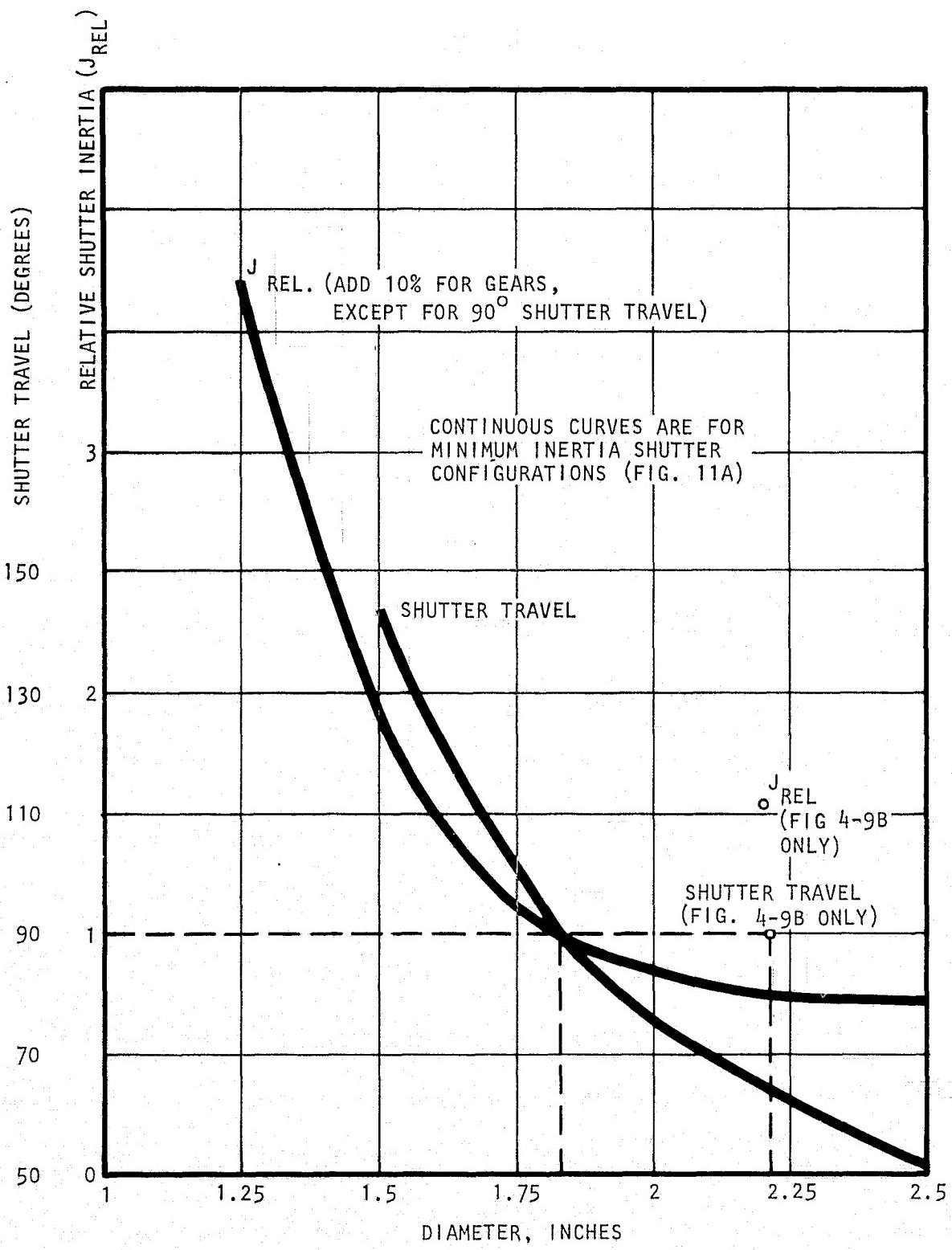


FIGURE 4-8. One Piece Shutter, Two Step Approach
Shutter Travel and Inertia vs Shutter Diameter

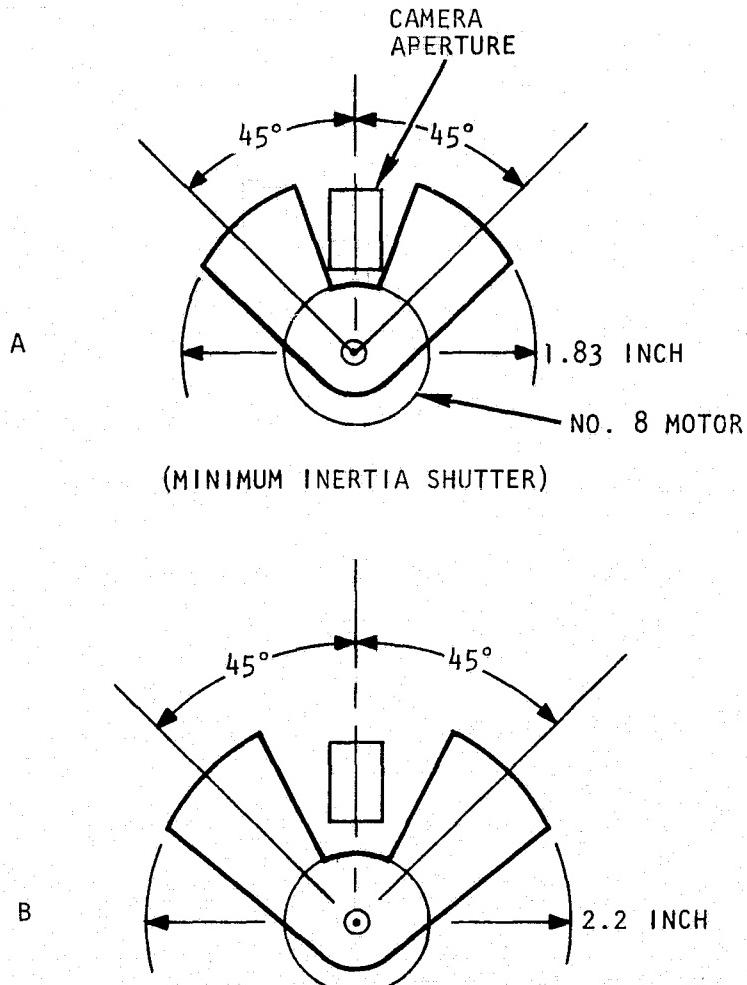


FIGURE 4-9. One Piece, 2 Step Shutter Configurations for Direct Drive From 45° Stepper

However, a new limitation is added. A 1/1000 second exposure time would require 1000 steps per second, not available in a number 8, 45° stepper motor. Elimination of this shutter speed is not considered a serious limitation, if the lowest exposure time can be reduced to 1/30 second, which would not present a problem except at 24 fps. At 24 fps, however, only 8.4 milliseconds would be available for film pull down, which is not compatible with a straightforward claw mechanism operating in the cine mode. Thus, this shutter approach is probably limited to exposure times of 1/30 to 1/500 second, with the further limitation that 1/30 second would not be available at 24 fps.

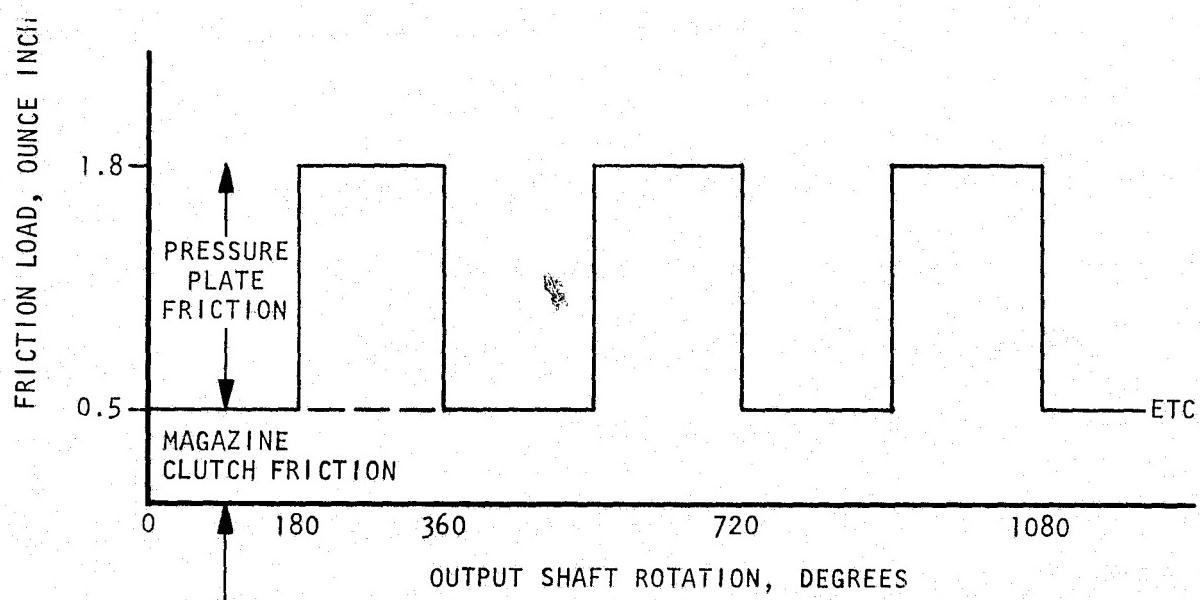
4.2.3 CLAW AND MAGAZINE DRIVE

As discussed earlier, precise positioning for the claw and film take-up in the magazine is not required. For the higher camer speeds, 6, 12, and 24 fps, the motor to drive these functions can be operated continuously at appropriately regulated speeds. For 2 fps and pulse mode, it could be operated in a start/stop fashion, the only requirement on position being that the claw always be brought to rest during the portion of the cycle when it is extracted from the film. A command from the electronics would start the cycle, and an internal signal triggered from a predetermined position of the claw would stop the motor. In this way, the claw drive could never creep towards a stop position where the claw would be engaged in the film. Thus, the master control of frame rate would be from the regulated speed of the claw drive for 6, 12, and 24 fps, and from timed start commands from the electronics for 2 fps. The shutter would be synchronized to the claw by a pulse from the claw system which would occur at a precise point after the claw becomes extracted from the film. This could be the same pulse that cuts power to the motor in the 2 fps and pulse modes.

The calculated worst case friction torque profile for the claw and magazine drive is shown in Figure 4-10. Because precise positioning is not a requirement, either a stepper motor or a brushless dc motor should be able to provide the claw and magazine drive requirements. The brushless dc motor, having characteristics comparable to the conventional dc motor, would have the necessary torque, speed, and speed regulation requirements and would offer better efficiency than the stepper motor. However, the present developmental nature of this type of motor, and lack of standardization in sizes and characteristics at this time, makes availability limited. Thus, looking at the stepper motor is also desirable.

In order to determine the suitability of a stepper motor for driving a claw mechanism, where a considerable portion of the load is friction rather than inertia, the breadboard shown in Figure 4-11 was fabricated and tested with 1 and 2 number 8, 15° stepper motors.

Using the same drive circuitry which was used for testing the breadboard of the conventional shutter, it was found that two number 8 motors could drive the mechanism in combinations 2, 3, and 4, but the performance for combinations 2 and 3 was marginal. An analysis similar to the one developed in Paragraph 4.1 was performed, and the results are plotted in Table 4-5 and Figure 4-12. Note that combination 4 is the only one where all points fall to the left of



△ - APPROXIMATE START AND STOP POINTS FOR 2 FPS
AND PULSE MODE OPERATION

FIGURE 4-10. Friction Load (Torque)
On Motor Output Shaft

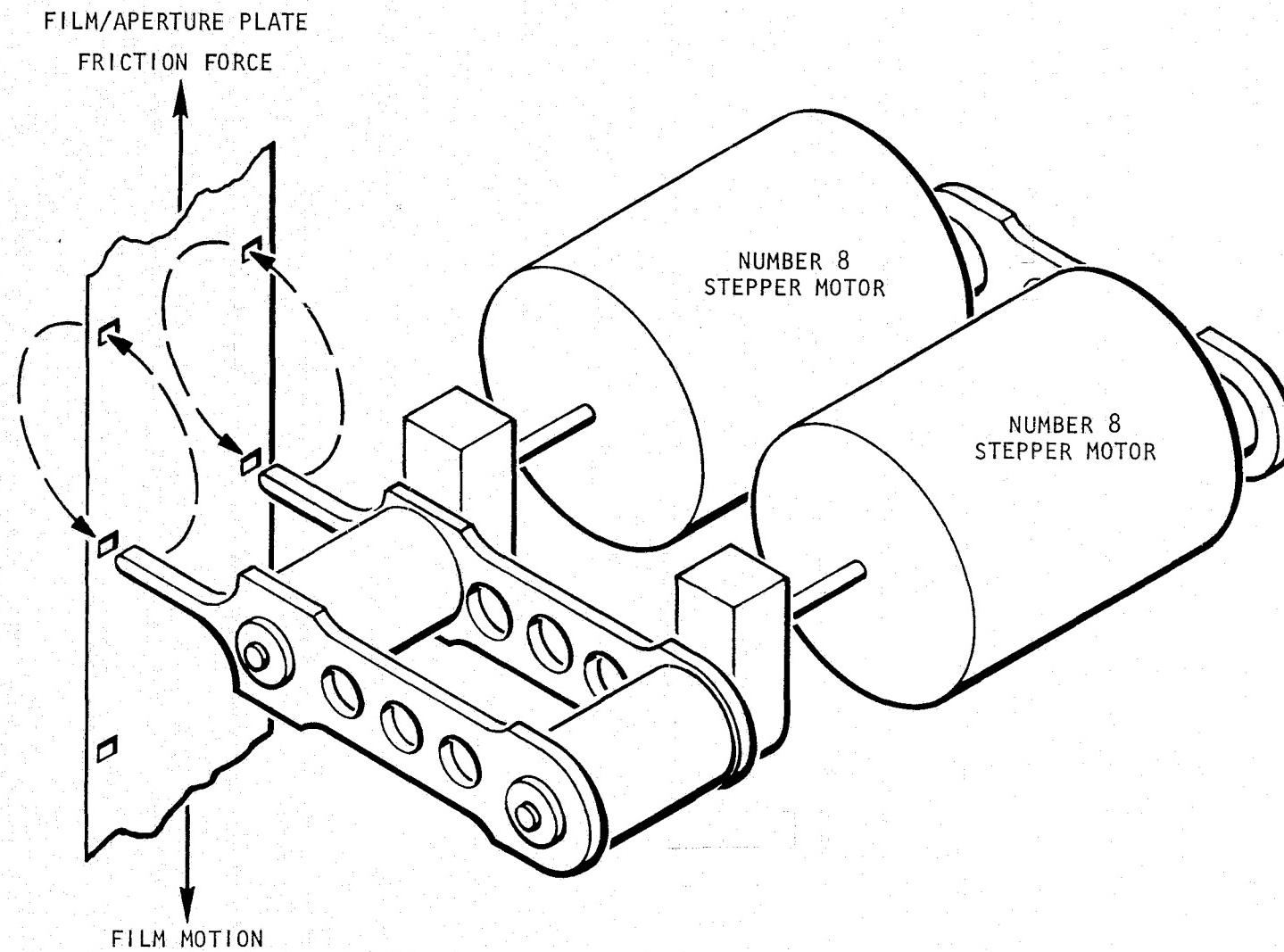


FIGURE 4-11. Breadboard Claw Mechanism

TABLE 4-5. Breadboard Claw Mechanism Torque Requirements
For Stepping Rate Transitions

| Combination (See Fig 4-2) | 1st Increment | | | | 2nd Increment | | | 3rd Increment | | | 4th Increment | | |
|------------------------------|---------------|-------|-------|-------|---------------|-------|-------|---------------|-------|-------|---------------|-------|-------|
| | C_0 | Steps | C_1 | T_1 | Steps | C_2 | T_2 | Steps | C_3 | T_3 | Steps | C_4 | T_4 |
| 2 | 0 | 12 | 192 | 0.191 | 12 | 576 | 1.15 | | | | | | |
| 3 | 0 | 6 | 144 | 0.108 | 6 | 288 | 1.14 | 12 | 576 | 0.861 | | | |
| 4 | 0 | 6 | 72 | 0.026 | 6 | 144 | 0.976 | 12 | 288 | 0.215 | 24 | 576 | 0.861 |

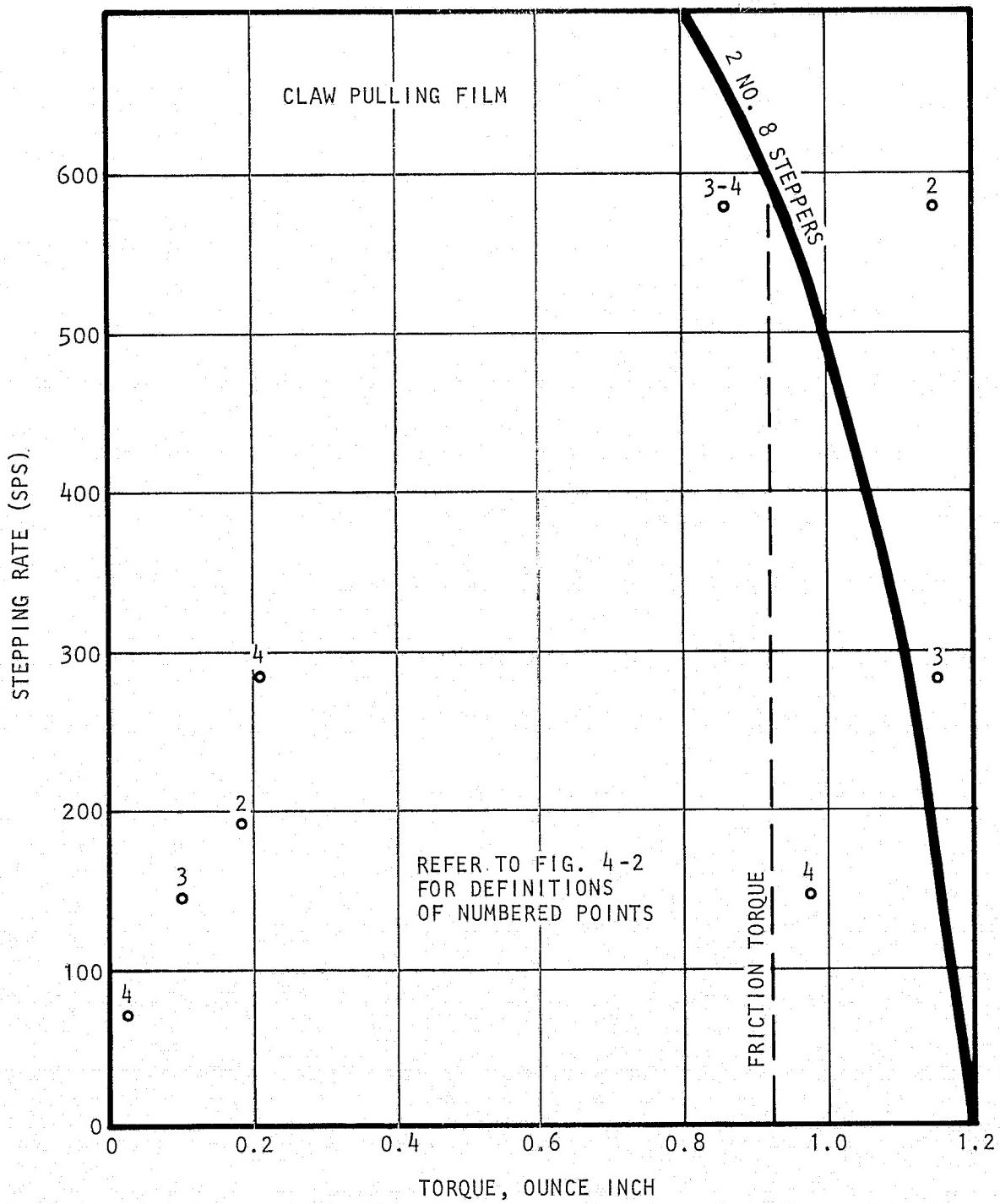


FIGURE 4-12. Transition Torque Requirements From Table 4-5
Compared With Stepper Motor Characteristic

the curve for two number 8 motors, while one point each for combinations 2 and 3 fall slightly to the right. From this, it is concluded that the analysis is quite accurate when the load is primarily frictional.

Since, in the system considered here, the claw and magazine will be run continuously at all speeds except 2 fps and the pulse mode, the acceleration and deceleration requirements will be greatly reduced, although the friction loads will remain the same. Analysis shows that a number 11, 15° stepper should be able to drive the combined claw and magazine in this manner.

A major disadvantage of a stepper motor in this application would be its low efficiency as compared to a brushless dc motor. This could possibly be overcome by providing switching to the motor windings based on shaft position feedback, rather than external commands when the motor is running in a speed regulated mode. Only in the 2 fps and pulse modes would it receive externally generated pulses. Thus, it would be running essentially as a commutated motor in all other cases, and the desirable features of the brushless dc motor would be obtained for conditions where this type of motor would be best, and stepper motor characteristics would be obtained for the intermittent motions where a stepper would be best. Another major advantage would be the ready availability of a stepper motor in the desired size.

5. SYSTEM BREADBOARD

The analysis and subsystem testing reported in Section 4 show the most promising approach if all of the requirements listed in Section 2 are rigidly adhered to is the one where a stepper motor drives the shutter and an electronically commutated dc motor drives the claw and magazine functions, with the two motors synchronized electrically.

In addition to eliminating the brush type motor and the clutch, this approach offers considerable simplification in the shutter control mechanism by eliminating the spur gear differential and the logarithmic cams or gears, the encoder, and the separate stepper motor required when an AEC is used.

If the requirement for independent shutter speeds and frame rates is taken out then the single motor drive using the electronically commutated DC motor becomes attractive because of its simplicity and reliability. The slower shutter speeds associated with the lower frame rates would be compensated by the automatic exposure control, through either the variable width shutter or the lens iris.

Of course, final judgement on both approaches must depend on testing of a complete camera breadboard. To meet this requirement in the most expeditious and economical manner, a standard DAC was modified to incorporate the features of the selected approaches. The following describes the modifications to the DAC and the electronic circuits used in the breadboard for the two motor approach. For the one motor drive approach, the shutter mechanism in the breadboard was returned to the original DAC design, and the shutter, claw, and magazine were all driven by the electronically commutated motor without using a clutch.

5.1 MECHANICAL DESCRIPTION

5.1.1 SHUTTER SUBSYSTEM

5.1.1.1 Stepper Motor

A Number 8, permanent magnet 90° stepper motor was determined by analysis to be best suited for the shutter drive. However, in subsystem testing with a standard off the shelf motor of this type, the rotor lost magnetism when the motor was pulsed with current sufficient to produce the necessary torque. Therefore, to meet the breadboard requirements, a special motor was ordered using samarium cobalt for the rotor permanent magnet material. Unlike the magnetic material in most standard motors, samarium cobalt will not lose magnetism even with the

heaviest current pulses which the motor can take. In order to get maximum torque from the motor, the motor stator is wound for standard motor 28 V performance on 15 V, so that when used on 28 V in the breadboard the motor produces considerably more torque than the standard motor. Overdriving the motor this way without damage is possible because the duty cycle (percentage of on-time to total-time) is very short.

Another feature of this motor is a second shaft extension that facilitates incorporating a shaft position detection device which is explained later in this section. The special motor is designated 08P-08A by the manufacturer (Computer Devices of California).

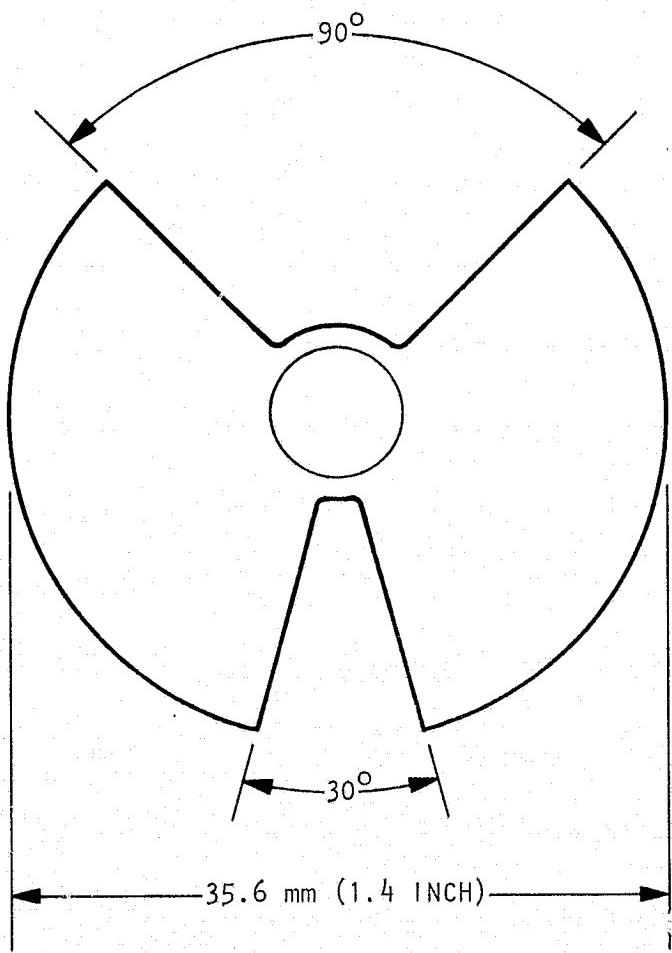
5.1.1.2 Shutter

A plan view of the shutter is shown in Figure 5-1. The shutter consists of a single piece, 35.6 mm (1.4 inch) in diameter, 2.54 mm (0.1 inch) larger than the DAC shutter to minimize the possibility of light leakage. As explained in Section 4, Paragraph 4.2.2.2, the 90° opening is used for time exposure and slower shutter speeds, while the 30° opening is used for the shorter exposure times.

One of the keys to the success of the stepper motor shutter drive approach is keeping the shutter mass moment of inertia to an absolute minimum. Since this value varies with the 4th power of the diameter, and the diameter is fixed by functional requirements, this is not an easy task. The obvious answer is to select a material of minimum density, and use the smallest practical thickness. Unfortunately, minimizing these two parameters simultaneously is not necessarily possible. For instance, steel offers one of the thinnest shutter designs, but is also one of the heaviest materials.

The lightest suitable metal is beryllium, and several structural plastics are slightly lighter than beryllium. A comparison of various suitable materials is shown in Figure 5-2. By selecting the minimum practical thickness for a particular material, the inertia of a shutter blade made from that material is quickly determined. Included in the inertia is the contribution of the drive between the motor and the shutter, described later in this report, and which also has been kept to a minimum. Points on Figure 5-2 indicate practical minimum inertias for shutters made of three materials, 0.12 mm (0.005 inch) thick beryllium, 0.178 mm (0.007 inch) thick SP-1 Vespel, and 0.178 mm (0.007 inch) thick mylar. The latter was used in preliminary tests because it was readily available, and shutters could be easily made from it.

The beryllium shutter was machined from 0.005 inch stock. Vespel is not available in sheet form, but the machining of the shutter from Vespel bar stock did not prove difficult. However, with the 0.007 inch thickness, some light is transmitted and spraying the shutter with a thin coat of black paint was necessary.



76-123

FIGURE 5-1. Shutter Blade

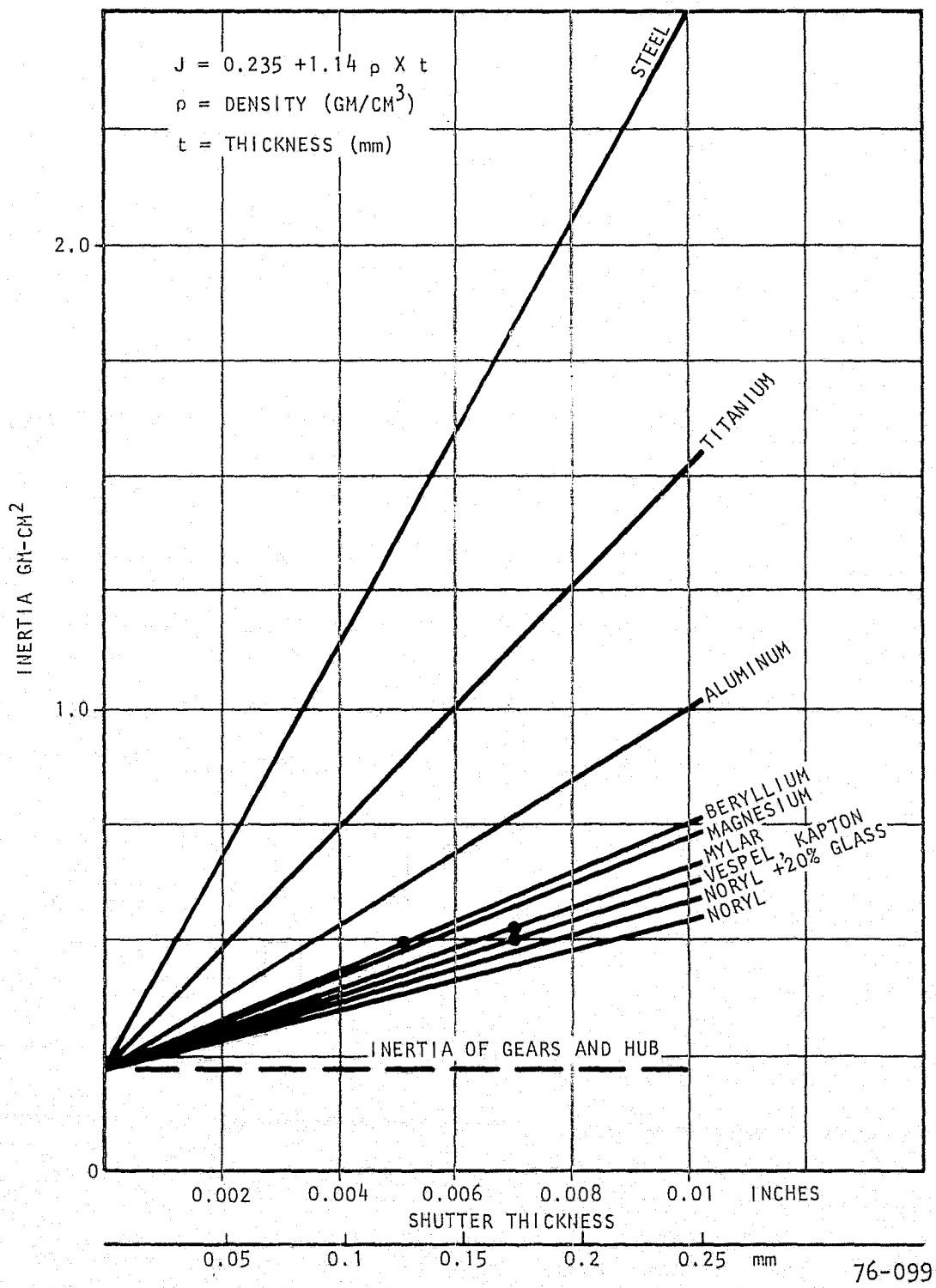


FIGURE 5-2. Comparison of Various Materials (See Figure 5-1)

5.1.1.3 Shutter Drive

For convenience in building the breadboard, the stepper motor is mounted to the front plate of the camera which also mounts the lens. In order to clear the lens, the motor center line is offset from the centerline of the shutter by 25 mm (1.0 inch), driving the shutter through the four gears removed from the spur gear differential of the DAC, which is no longer required. This arrangement is shown in Figures 5-3 and 5-6. Bearing and bearing supports were also salvaged from the DAC, including the shutter post which remains at the same location.

This arrangement allows sufficient clearance to allow use of two of the standard DAC lenses (5 and 10 mm). In future designs this limitation can be overcome by incorporating the stepper in the body of the camera.

5.1.1.4 Shutter Position Monitor

For proper control of the stepper motor, electrical signals are required to indicate certain shutter positions. These are obtained from a shaft position detector that is attached to the opposite end of the stepper from the pinion, forward of the camera. One signal is required for precise control of the second motor step when using the 30° shutter opening to achieve uniform shutter speed throughout exposure. A second signal controls the retarding pulses at the completion of exposure to limit overshoot and prevent additional light from reaching the film plane after the shutter is supposed to be closed. A third signal is required to tell the electronics that the shutter is oriented either for the large opening or the small opening. The relationships of these signals to shutter position are shown in Figure 5-4.

All three signals are obtained from the device shown in Figure 5-5. One slit provides the signal which controls the pulse for the second motor step, and two slits at 90° provide signals for controlling overshoot. These signals occur when the slits line up with infrared Light Emitting Diodes (LED) and photodarlington sensors. The shutter orientation signal is provided by detecting differences in reflected energy from dark and light areas on the rotating shaft.

The LED and photodarlington sensors are mounted on small circuit boards that attach to a holder which mates with the end of the motor frame. The shaft position detectors are easily brought into proper phase relation with the shutter by rotating this holder and locking it with a setscrew.

5.1.2 CLAW AND MAGAZINE DRIVE SUBSYSTEM

5.1.2.1 Motor

The two major performance considerations for this motor are that it deliver sufficient power at appropriate regulated speeds for the higher frame rates, and to drive the claw and magazine one frame at a time at the slower frame rates and in the pulse mode. The motor selected for this application is a Siemens Corporation type 1AD3004 brushless dc motor, which uses built in Hall

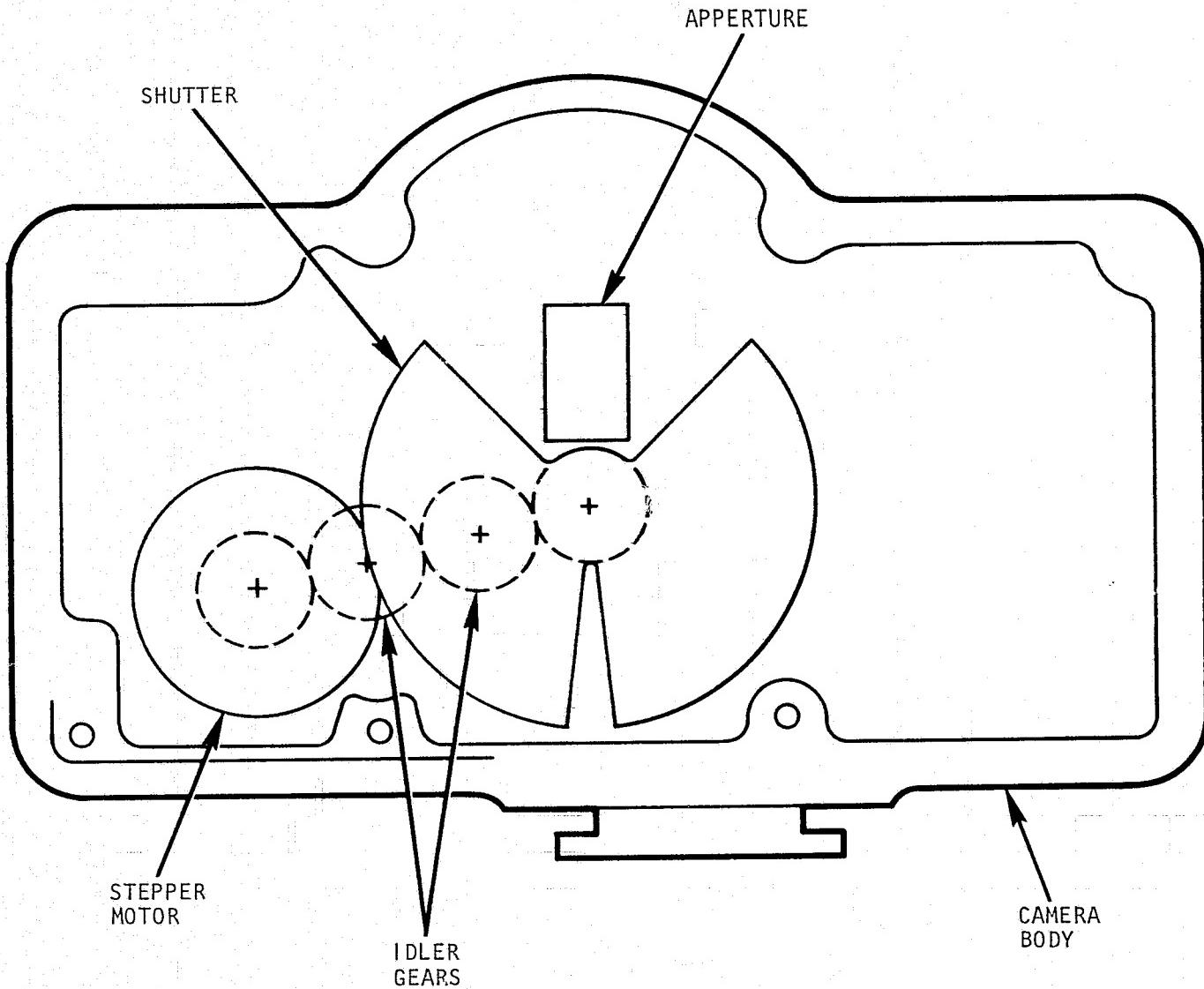
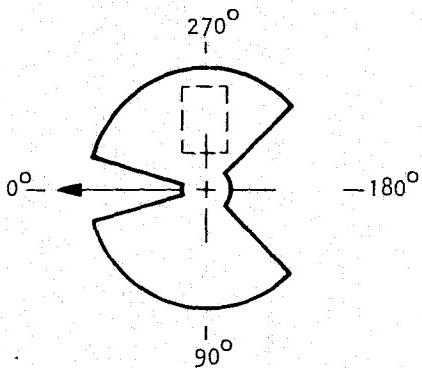
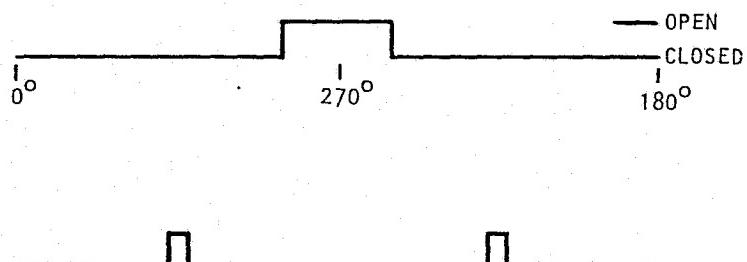
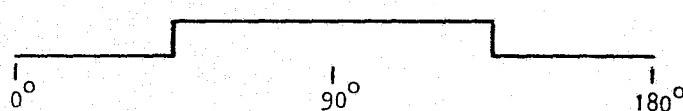


FIGURE 5-3. Shutter Drive

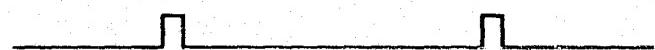
76-122



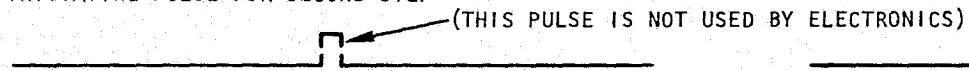
SHUTTER POSITION



RETRO-TORQUE PULSES



INITIATING PULSE FOR SECOND STEP



SHUTTER ORIENTATION SIGNAL



76-100

FIGURE 5-4. Timing Diagrams for Shutter Position Detector Outputs
(Referenced to Smaller Shutter Opening)

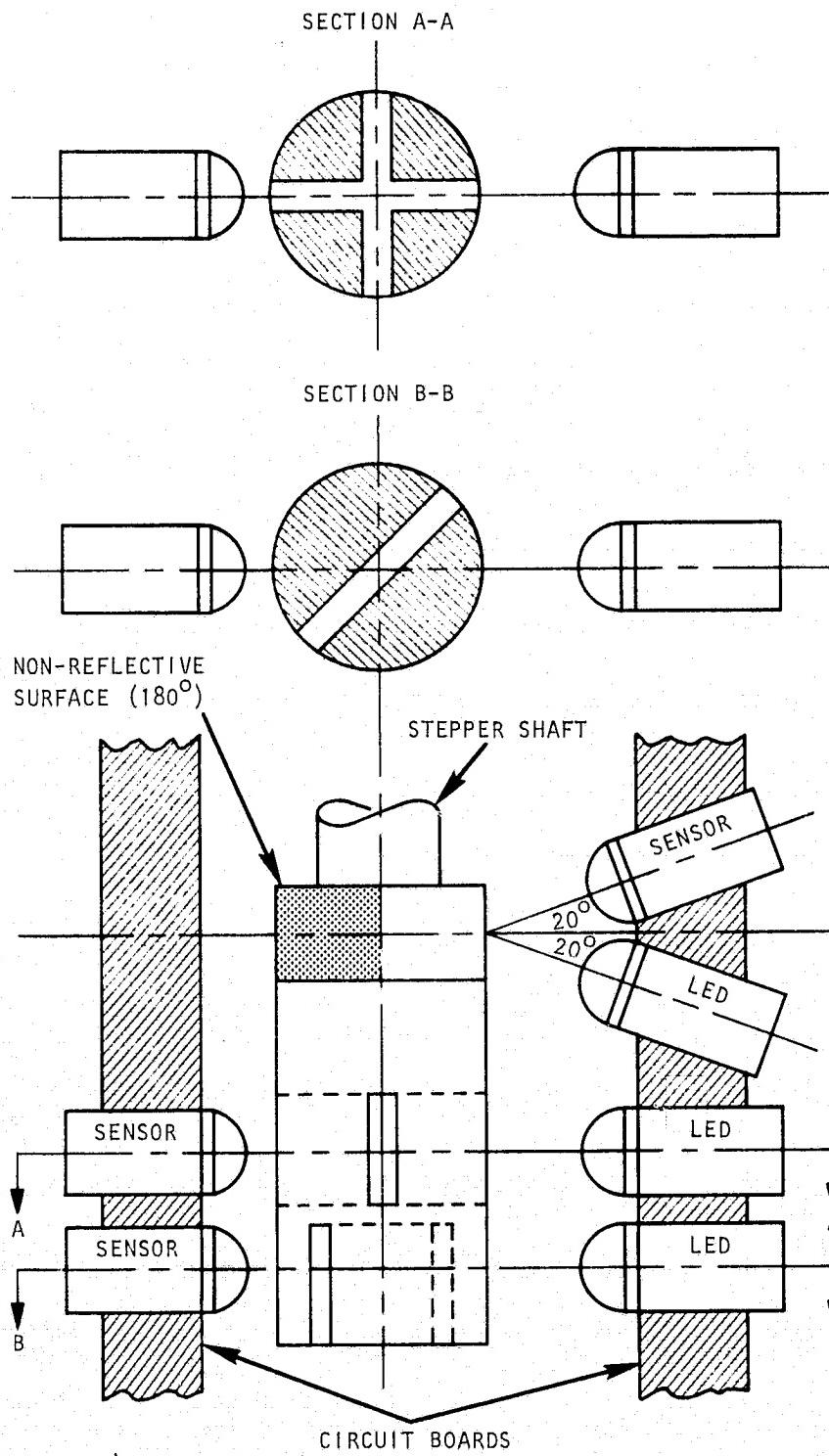


FIGURE 5-5. Shutter Position Detector

effect devices for controlling commutation. This motor was selected for the breadboard for its performance, price, and fast delivery. Although the motor diameter, 28 mm (1.1 inches), is too large to fit inside the standard DAC camera body, its performance characteristics are well suited for the breadboard. Siemens makes a motor of the same type in a smaller frame size that would fit in the camera and provide the necessary performance, but it was not available in time for completion of this study without delaying the schedule.

5.1.2.2 Claw and Magazine Motor Drive

Figure 5-6 shows the installation of the Siemens motor in the DAC. A slot was cut in the camera body to accommodate the 28 mm motor diameter. In order that the motor operate at speeds for best performance, a two stage four to one gear reduction connects the motor shaft to the input to the DAC clutch. The clutch was modified to be permanently engaged, serving only as a coupling to the front of the camera. The shutter was uncoupled from this drive and connected to the stepper motor by moving two of the shutter gears from position 1 to position 2, as shown in the figure. The claw and magazine are driven by the standard DAC gear train.

5.1.2.3 Sync Signal

A position signal from the claw and magazine drive is required for two purposes; (1) a signal to turn off the motor when it is operating in a pulse type mode and, (2) a signal to trigger the shutter drive when the claw is first disengaged from the film. One position signal supplies both functions. This signal is generated by a Spectronics SPX-1160 reflective sensor assembly, which senses a dark stripe on the face of the drive gear that is attached to the input of the permanently engaged clutch.

5.1.3 TEST FIXTURES

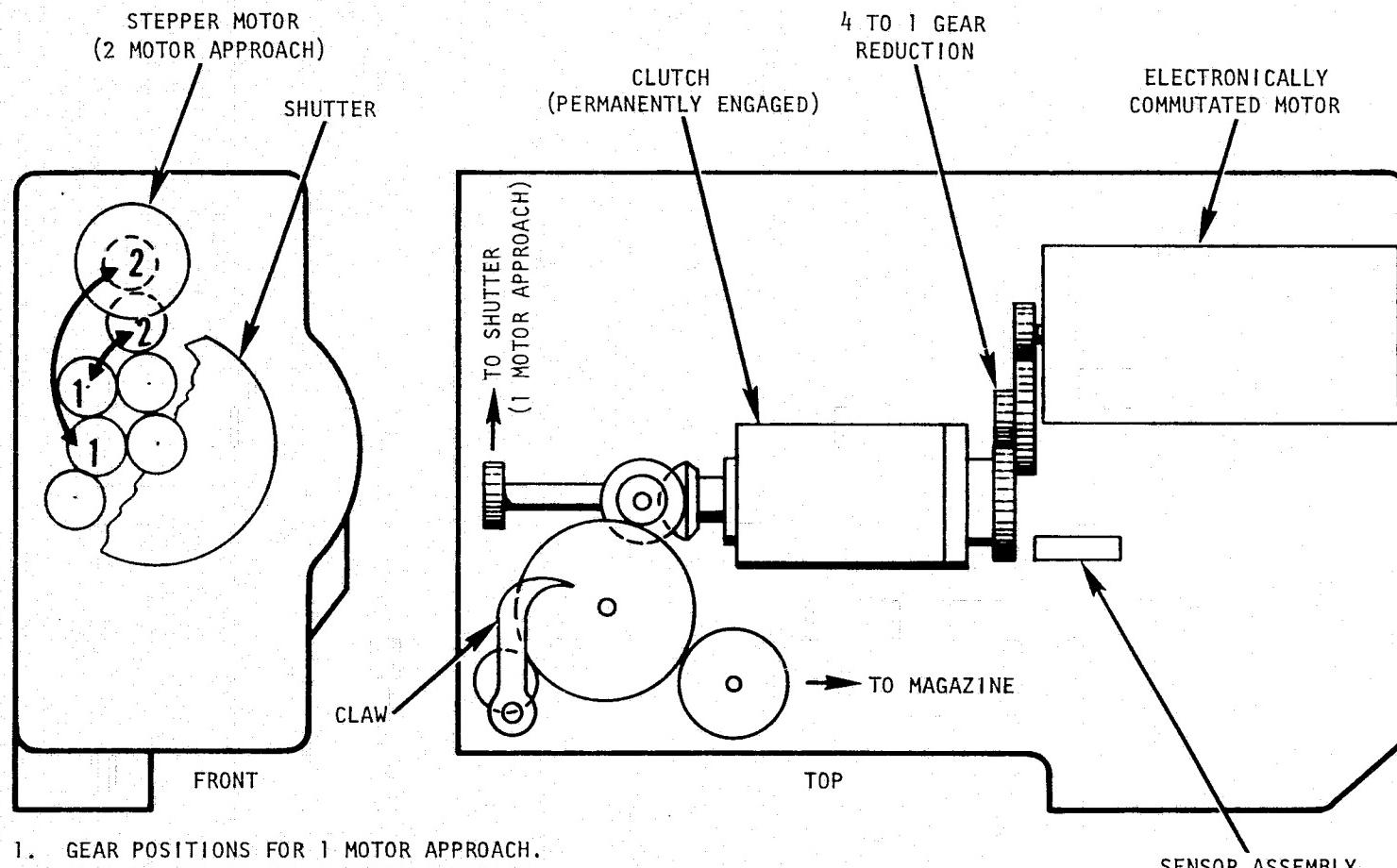
5.1.3.1 Shutter Accuracy

An accessory was developed for easily and precisely checking the accuracy of the shutter speed and uniformity of velocity during exposure. This accessory consists of a Vespel block which fits closely in the camera aperture from the magazine side, as shown in Figure 5-7. Seven 0.9 mm (0.035 inch) diameter holes are accurately drilled in this block at the four corners of the aperture and midway on three sides. Phototransistors mounted in back of these holes detect the passage of shutter opening and closing edges.

5.2 ELECTRONICS DESCRIPTION

5.2.1 GENERAL

The electronics necessary for implementation of the dual motor drive scheme are shown in Figures 5-8 and 5-9. The only common connections for the two motor drive circuits are the trigger switch, time exposure switch, film advance pulse, and power input. Each drive system will therefore be discussed on an individual basis.



1. GEAR POSITIONS FOR 1 MOTOR APPROACH.
2. GEAR POSITIONS FOR 2 MOTOR APPROACH.

76-116

FIGURE 5-6. Motor and Gearing Installations

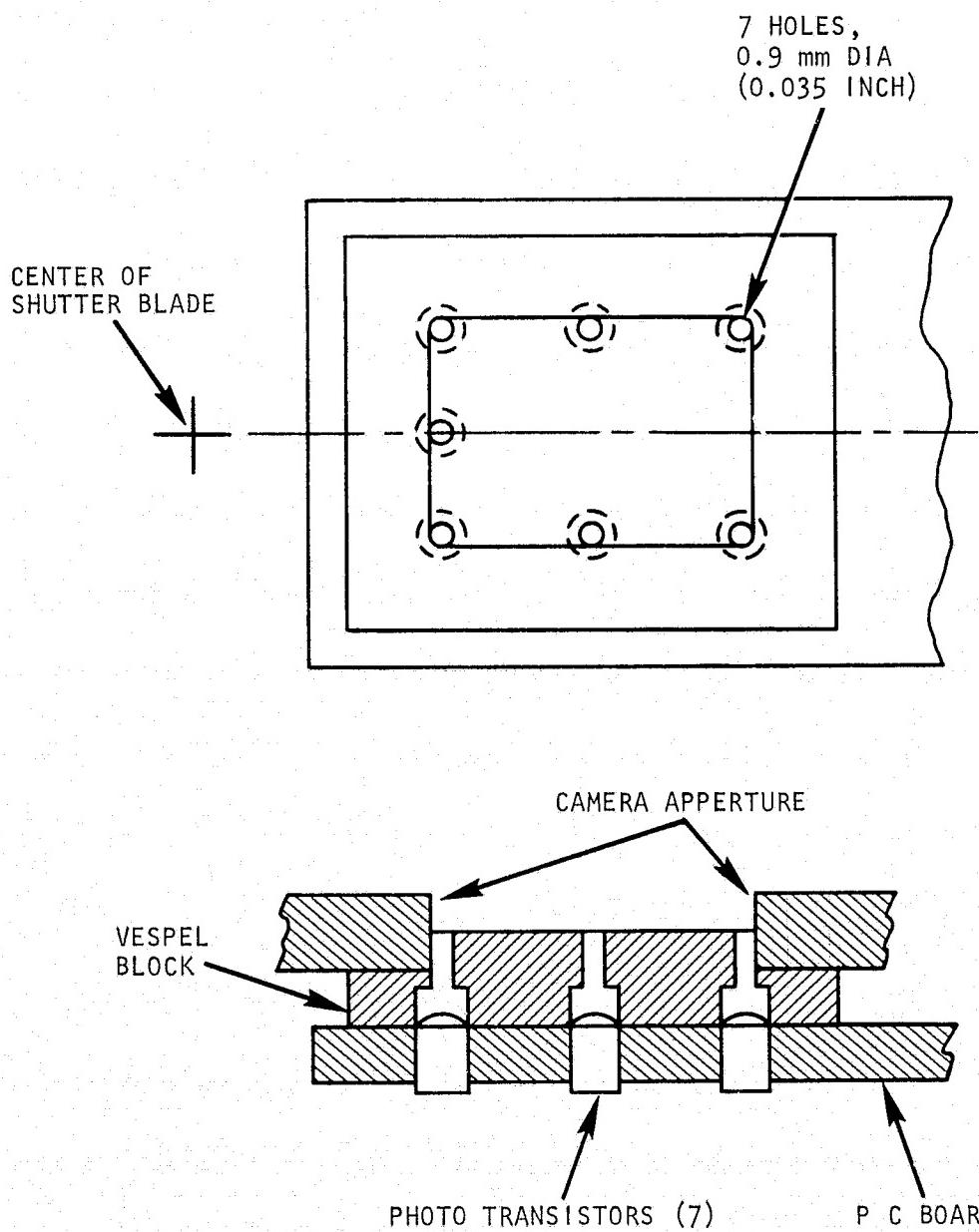
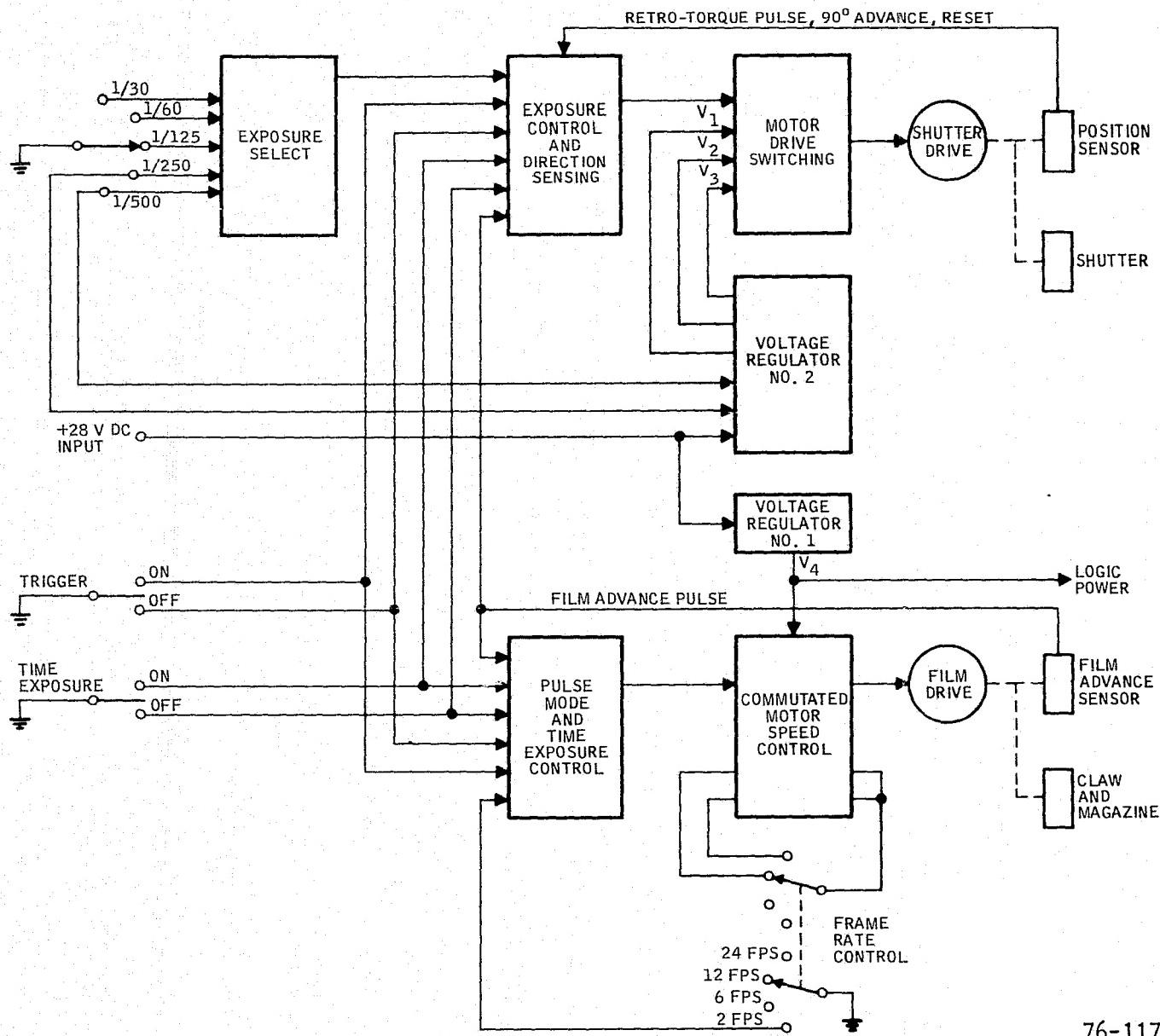


FIGURE 5-7. Shutter Speed Test Fixture

76-126



76-117

FIGURE 5-8. Film and Shutter Drive Functional Block Diagram

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

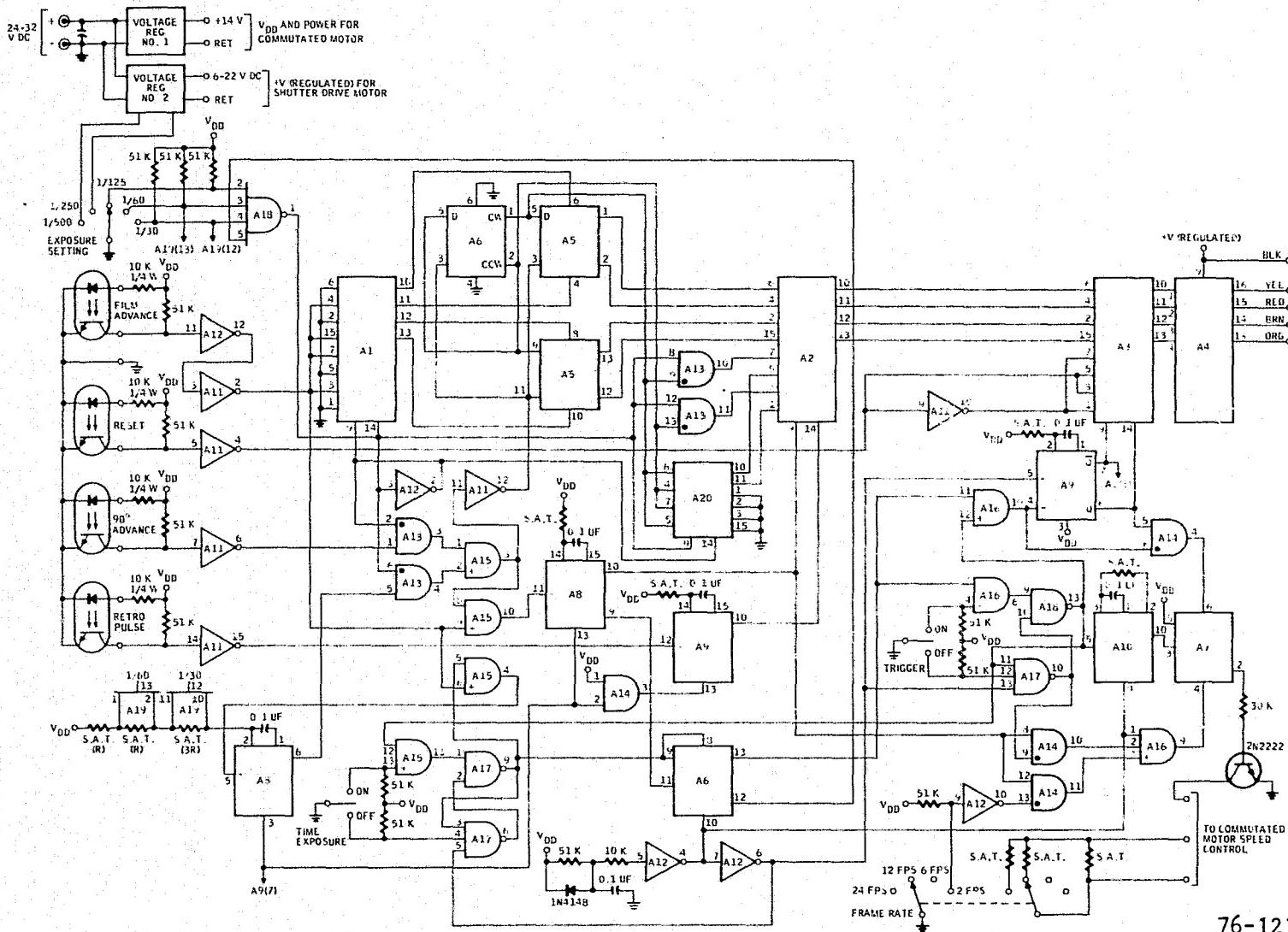


FIGURE 5-9. Electronic Dual Motor Drive Schematic

76-121

5.2.1.1 Shutter Drive Electronics

The shutter drive electronics has two basic requirements; exposure control and synchronization capability with the film drive system. To satisfy these requirements, circuitry is provided to accept digital input levels (logic "0") from the exposure select switch and convert this information to a corresponding exposure time. Since two shutter openings are involved, circuitry is also necessary to sense direction and position of the openings based on the exposure setting selected. The motor drive switching network accepts direction and time phased inputs along with one of three regulated voltages. The outputs of the motor drive switches are properly phased dual winding drive signals capable of stepping a 90° bidirectional stepper motor.

5.2.1.2 Shutter Drive Operation - Slow Exposure (1/30, 1/60, 1/125 second)

The actual circuit operation is best described by the timing diagrams shown in Figures 5-10 and 5-11. Using Figure 5-10, assume that a 1/125 second exposure has been selected and the shutter is in an unknown position. When the trigger is applied, the sensor that monitors the position of the large and small opening is immediately sampled. If the reference point on the shutter is between 0 and 270°, or between 0 and 90°, a reset pulse is applied to the red/brown motor windings which pulls the shutter to the 0° position. If the reference point on the shutter is between 90 and 180°, or between 180 and 270°, a reset pulse is applied to the yellow/orange windings and the shutter is pulled to the 180° position. This ensures that once the system is triggered, the shutter is oriented properly and that it takes the shortest path to obtain this orientation.

The shutter remains in a closed position until the film advance signal is received from the sensor which monitors the claw and magazine drive. This signal is phased such that the leading edge occurs just after the claw has retracted and the film is stationary. The trailing edge of the signal initiates the cycle shown in Figure 5-10. Assuming the shutter has started from the 0° reference point, the yellow and brown windings are energized as shown and the reference point on the shutter rotates counterclockwise toward the 90° point. This in turn rotates the large opening toward the aperture. At the 45° point, the sensor that supplies the retro-torque signal is energized and applies a retarding pulse to the red winding. This pulse forces the shutter to begin slowing down such that it does not overshoot by more than 10°, and subsequently comes to rest prior to the exposure time (8 milliseconds) elapsing. At the completion of the exposure time, a second motor step is taken with the appropriate windings energized and retro-torque pulse applied such that the reference point on the shutter comes to rest at the 180° point. This completes one exposure. On receipt of the next film advance pulse, the above two step process is repeated, but the reference point on the shutter now rotates clockwise from 180 to 0°. This again brings the large opening in front of the aperture. This cycle continues at a repetition rate based on the frame rate selected.

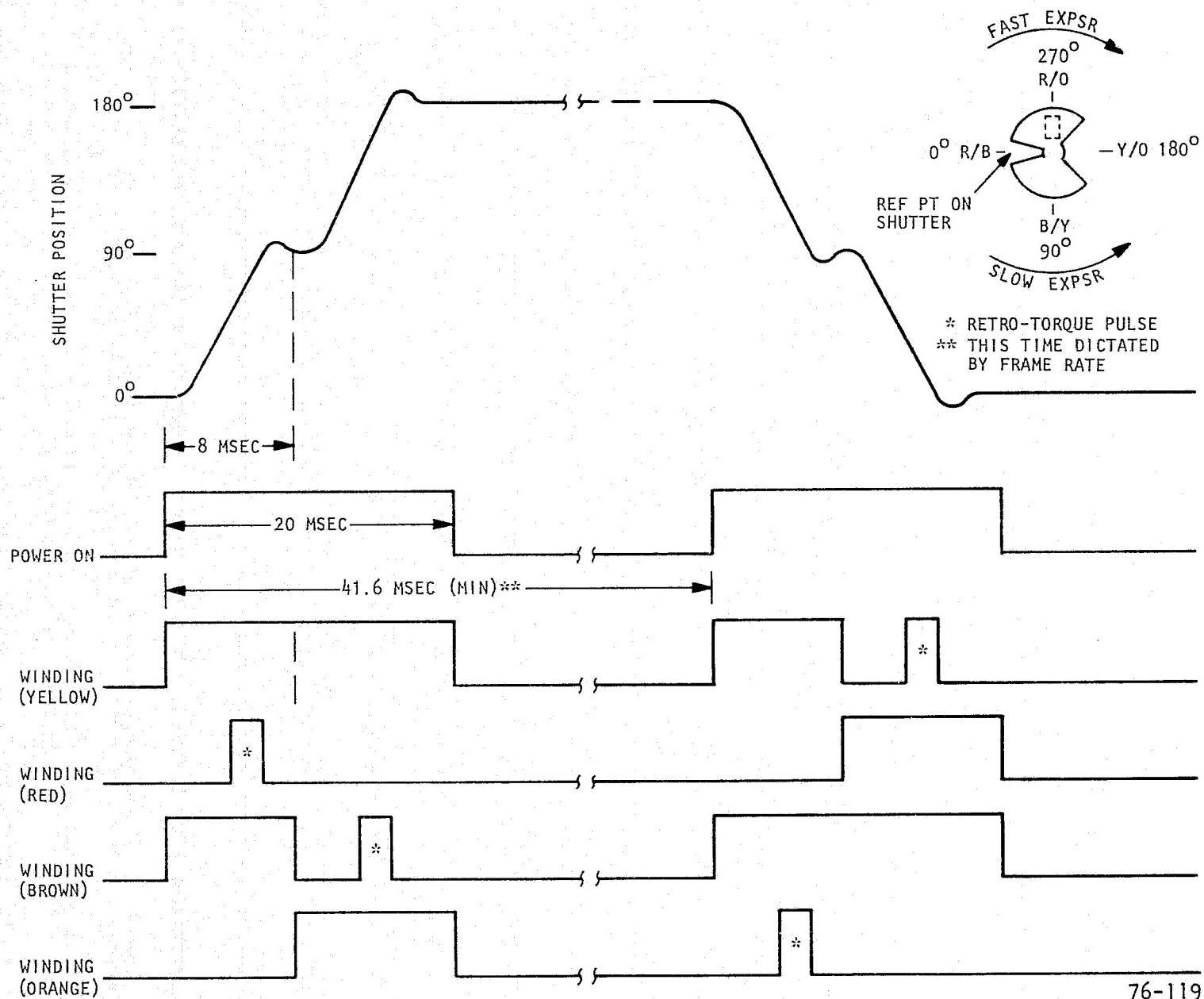


FIGURE 5-10. Timing Diagram - Shutter Drive (1/125 Second Exposure)

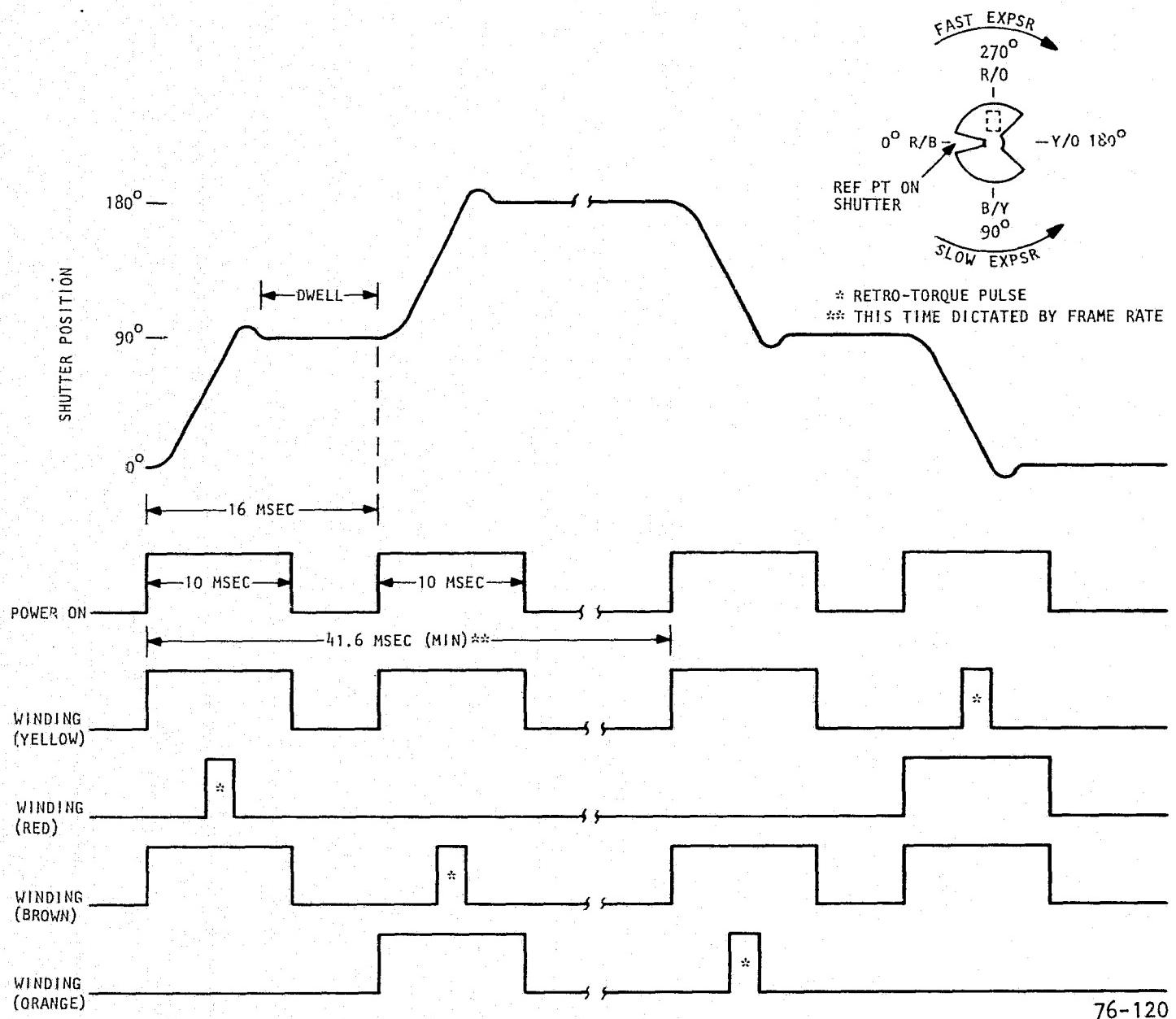


FIGURE 5-11. Timing Diagram - Shutter Drive (1/60 Second Exposure)

A second timing diagram (Figure 5-11) shows a 1/60 second exposure. The only differences between operation for the 1/60 second exposure and the 1/125 second exposure already discussed are the dwell time (i.e., the shutter is at rest in the open position longer), and the power cycle. Power for this exposure is turned off during the portion of the dwell cycle after the first 90° step has been completed. Note that in both cases power is applied for a maximum of 20 milliseconds, which results in a duty cycle of approximately 50% at the fastest frame rate (24 fps) and would reduce proportionately at the lower frame rates.

All three of the slow exposures (1/30, 1/60, 1/125 second) utilize a regulated voltage of +22 V dc for stepping the motor. This is accomplished simply by leaving the two voltage regulator control inputs in the open position when the respective exposure is selected.

5.2.1.3 Shutter Drive Operation (Fast Exposure (1/250, 1/500 second))

Previous testing has indicated that attempting to step and stop even the lightest inertial loads at two and four milliseconds is not practical. The slow exposure technique is therefore modified somewhat to obtain the faster exposures. The basic differences are: (1) the second 90° step is applied by sensing 90° position feedback rather than time, (2) the first 45° retro-torque pulse is not applied and, (3) a regulated voltage together with a known fixed opening determines the exposure time.

Referring to Figure 5-12, and again assuming a trigger from the 0° reference point, power is applied to the red/orange windings which rotates the 0° reference point clockwise toward 270°. This rotates the small opening toward the aperture. However, the first 45° retro-torque pulse is inhibited and the shutter continues to rotate. After 90° of rotation, the shutter advance position sensor energizes, which in turn causes the motor drive circuit to apply power to the yellow/orange windings. This keeps the motor rotating at a constant speed governed only by the regulated voltage applied. The second 45° retro-torque pulse is then utilized to slow and stop the motor such that it comes to rest at the 180° point. This process is then repeated with the 0° reference point (small shutter opening) rotating counterclockwise toward 0° for the second exposure. Again this repetition rate is determined by the frame rate selected. The only difference between the 1/250 second and 1/500 second exposure requirements is the regulated voltage. Changing this voltage causes the slope (rate of change) of the shutter to operate at the appropriate exposure selected.

5.2.1.4 Shutter Drive Operation (Time Exposure)

This exposure is accomplished simply by momentarily actuating the time exposure switch to ON. This causes the magazine and claw mechanism to advance one frame. When the claw retracts, the film advance pulse is again utilized to trigger the shutter drive electronics, which in turn energizes the proper motor windings to step the large shutter opening in front of the aperture. The shutter remains in this position until a second pulse is generated by momentarily actuating the time exposure switch to OFF. This action generates a second pulse which advances the shutter to the closed position.

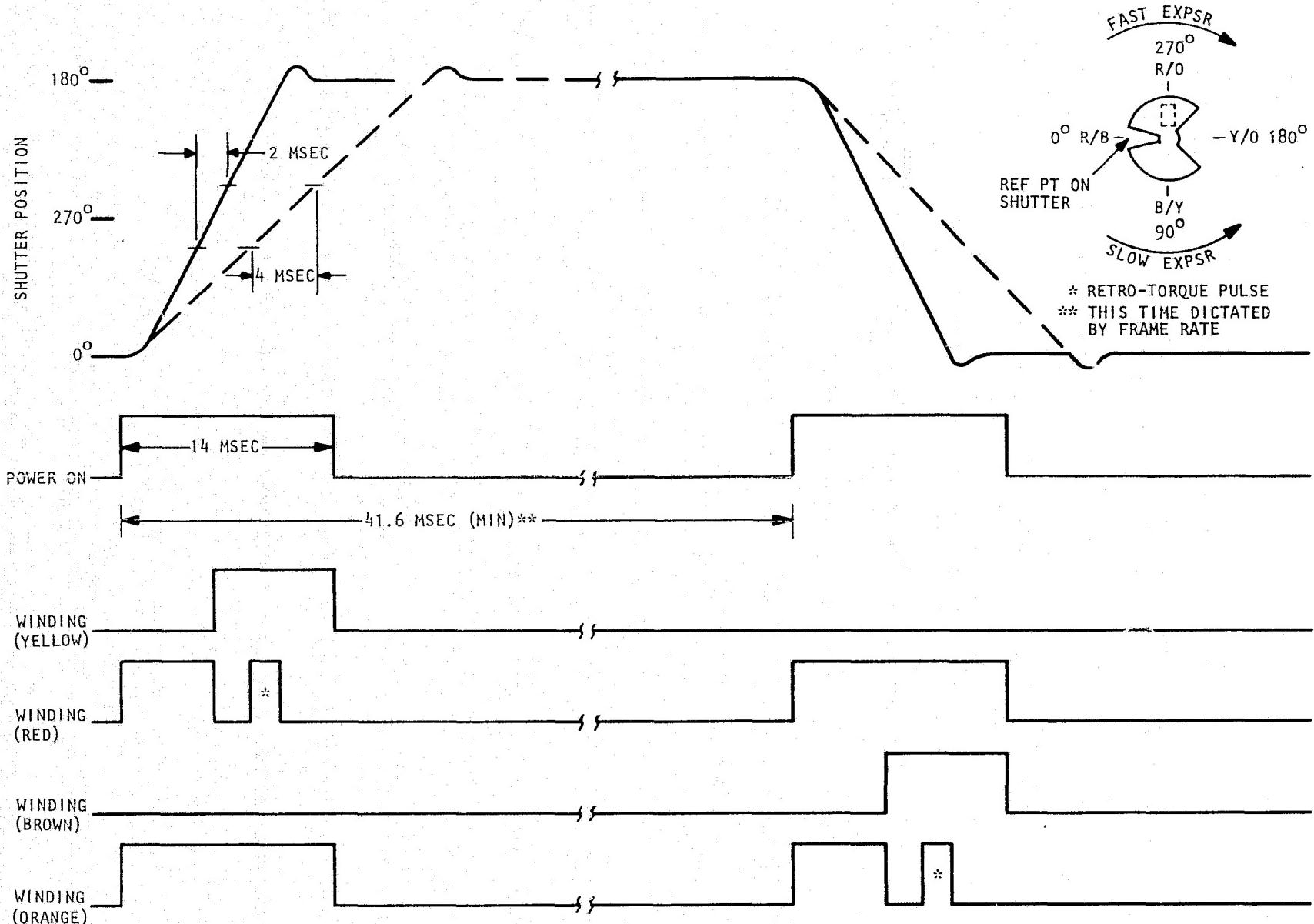


FIGURE 5-12. Timing Diagram - Shutter Drive (1/500 Second Exposure)

5.2.1.5 Shutter Drive Circuit Components

The circuit components for the shutter drive electronics are primarily digital (COS/MOS), except for the voltage regulator and motor drive transistors. Exposure timing and various pulse widths (reset, retro-torque, shutter advance, and power on) are obtained by the use of two dual one shots. Direction sensing and proper phasing for the windings is accomplished by the use of two dual D flip flops and an AND/OR select gate. Three additional AND/OR select gates are utilized to control application of the retro-torque pulses and reset pulses to the appropriate windings. The decision to use one shots was made primarily to provide some flexibility in varying the pulse widths during breadboard testing. An oscillator and digital programmable counter combination would probably be used in a final design to provide the necessary timing.

5.2.1.6 Claw And Magazine Drive Electronics

The electronics necessary for control of the claw and magazine drive are shown in Figure 5-8. To meet the requirement of variable frame rates for 6, 12, and 24 fps, a voltage regulator and commutated motor speed control circuit are utilized. For pulse mode and time exposure control, a simple intervalometer provides ON/OFF signals to control application of power to the commutated motor. As discussed in Paragraph 5.1.2.1, a Siemens Corp, type IAD3004 brushless dc motor was chosen for the system breadboard. To further expedite development during this phase, an off the shelf speed control circuit (TK 36999) was purchased from Siemens Corp. The only additional electronics required to implement this motor in the total system were; (1) a voltage regulator, (2) external switching to change speeds, and (3) an intervalometer and control switch to operate in the pulse mode and start/stop the motor.

5.2.1.7 Claw And Magazine Drive Speed Control (Cinemode)

The standard speed control circuit purchased from Siemens utilizes a combination of two Hall generators, four preamplifier transistors and four power transistors to provide 90° commutation. This commutation scheme is basically the same as the two phase system discussed in Section 3, Suitable Motor Types.

During startup, the preamplifier transistor with the highest base voltage (Hall signal) turns on and in turn applies power to the proper winding. Each winding conducts current during 90° with only one winding energized at a given time. The current wave shape is basically a squarewave. During the time a winding circuit is energized, the phase displacement between the vectors of the rotor and stator fluxes changes from 45 through 90 to 135° . Accordingly, the torque pulsates between $0.71 T_m$ and T_m four times over one revolution.

To obtain speed control, a simple circuit is used to sense the speed of the motor, therefore eliminating the need for a tachometer. The actual speed signal value is obtained by decoupling the generated back EMF through four diodes during no current conduction periods of the respective windings. The Hall generators are supplied with a fixed control current. A zener diode establishes a reference current which is compared against the feedback signal and the resulting error provides a variable current source to the preamplifiers.

The output of the preamplifiers drive the power transistors to maintain constant speed. To obtain variable speeds (i.e., 6, 12, and 24 fps), the fixed reference current is changed by selecting different resistor values. In the breadboard system, this selection is made externally by maintaining one resistor in the circuit path at all times and paralleling this value for higher speeds. This insures that the loop is always closed and allows for smooth transition from one speed selection to the next.

The speed control method described above is very economical, since the motor is used as a motor and tachometer at the same time. The basic disadvantages are lack of precise speed regulation over the full temperature range and the necessity for four large power transistors in series with the windings. The manufacturer specifies the speed regulation of this circuit at $\pm 2\%$ over the full torque range, a temperature range of -10 to +55°C, and a supply voltage range of $\pm 10\%$.

To obtain the $\pm 1\%$ speed regulation required in the specification, a combination phase lock loop and tachometer feedback would probably be necessary. To eliminate the large power transistors, a saturated switch design would be required encompassing either pulse width modulation or the use of a single power transistor in series with the common input to the motor for speed regulation, and four small transistor switches for commutation. Optical commutation would also be desirable since the Hall effect devices are somewhat temperature sensitive and, according to some manufacturers, less reliable.

5.2.1.8 Claw And Magazine Drive Speed Control (Pulse And Time Exposure)

In the previous discussion, a means for obtaining the various cinemode speeds was described. To obtain the lower frame rates, a pulses mode technique was implemented which would allow starting and stopping the motor without using a clutch/solenoid combination. The circuitry required to accomplish this consists of an oscillator to establish the frame rate, a flip flop to control the power cycle, a transistor switch to interface with the speed control circuit, and the same film advance sensor already described under shutter operation.

On receipt of the trigger signal the flip flop is set, which turns the transistor switch off and allows the reference current in the speed control circuit to flow. This current is set for an equivalent speed of 6 fps. At the same time, the oscillator is enabled and the first cycle (500 ms for 2 fps) is initiated. When the claw has reached that point in the cycle which triggers the film advance sensor, the flip flop is reset and power to the motor is removed by the transistor switch that turns on and shunts the reference current. At completion of the first oscillator cycle, the flip flop is again set and the entire pattern repeated. Pulse mode operation is thus obtained by applying power at a fixed clock rate and removing power at an appropriate point in the mechanical cycle such that the motor comes to rest by system friction.

Selecting time exposure causes a similar cycle to take place, but the oscillator is not allowed to run. When the flip flop is reset after the first film advance pulse, a trigger signal is not available to set the flip flop and reinitiate the power cycle. This results in only one film frame being pulled in front of the aperture until another time exposure command is received.

6. SUMMARY AND CONCLUSIONS

The primary goal of this study is to eliminate the brush type dc motor and the clutch from the 16 mm space sequential camera design by replacing them with one or two brushless type dc motors. Another requirement is that as many of the standard DAC desirable features as possible be retained, including independent shutter speeds and frame rates. An investigation was made of dc brushless motor types that would be suitable for this application. From these, two were selected as most promising, the stepper motor and the electronically commutated dc motor.

The stepper motor provides precise positioning, but is relatively inefficient and lacks the speed/torque capabilities of the electronically commutated motor.

The electronically commutated motor offers performance characteristics equivalent to the brush type motor, but without its inherent weaknesses. The elimination of the clutch from the camera, however, makes a direct replacement of the brush type motor with this type of brushless motor impractical, unless the requirement for independent shutter speeds and frame rates is removed.

Various camera system applications using these two types of brushless motors, both individually and in combination, were studied and are discussed in this report. This study shows that one of the most promising approaches is where a stepper motor drives the shutter and an electronically commutated dc motor drives the claw and magazine drive functions. The two motors are synchronized electrically.

In addition to eliminating the brush type motor and the clutch, this approach offers considerable simplification in the shutter control mechanism by eliminating the spur gear differential and the logarithmic cams or gears, the encoder, and the separate stepper motor required when an AEC is used.

An average current of 300 milliamperes for the film drive appears attainable for this approach. The AEC shutter motor would be eliminated by going to the stepper motor/fixed opening shutter combination, requiring an average current of not more than 400 milliamperes for the shutter motor at 24 fps. This current would drop proportionally at the lower frame rates (i.e., at 12 fps it would be 200 milliamperes, etc.). By including an iris drive motor in the AEC, which draws power only when a light change takes place, the average current for all three motors when operating at 24 fps would probably not exceed 750 milliamperes, with a peak current of less than 1-1/2 ampere.

Without the requirement for independent shutter speeds and frame rates, driving all of the camera functions with a single electronically commutated motor becomes feasible without using the clutch. Preliminary breadboard testing has shown that achieving the 6, 12, and 24 fps frame rates is possible by controlling the speed of the motor. Two fps and time exposure are achieved by running the motor in a pulse mode. The average current would be about 400 milliamperes.

One possible problem with this approach, which will be checked out in further testing on the breadboard, is that the shutter speed may not be sufficiently constant in the pulse mode during the time when the shutter is opening and closing. The cycle is accomplished by starting with the pulling of the film by the claw, which occurs while the shutter is closed. During this time the motor should come up to the required constant speed before the shutter opens. If stopping the motor and drive in the required time becomes a problem, a retarding pulse to the motor will be applied. At the present time, friction in the system appears sufficient for this function.

One of the implications of the shutter speed not being independent of frame rate is that the shutter opening must be reduced each time the frame rate is decreased, so that the shutter speed and film exposure will remain constant. If the shutter speed is less important, the exposure can also be kept constant by stopping down the lens iris. These compensations can easily be designed into the automatic exposure control system.

Another implication of this mode of operation is that two f stops at the short end of the exposure range will be lost at 6 fps, because the shutter will be operating at 1/4 its base speed (which is associated with 24 fps). At 12 fps, one exposure range f stop would be lost. Overcoming this problem might be possible by designing the variable opening shutter for two more stops at the small opening end. However, mechanical design limitations make this possibility unlikely.

The final recommendation on which approach to take will ultimately depend on the outcome of breadboard testing. Current thinking is that the two motor approach is definitely feasible based on breadboard testing to date, but there are a number of details and refinements which must be worked out before it would be safe to commit the concept to final design.

The one motor approach, being closer to the concepts which are well established in the DAC design, would require less development effort before final design could begin. It also can be adapted to higher frame rates at a later time, if desired. (This is a limitation with the two motor approach, as discussed in the last paragraph of Section 4.2.2.2). However, this approach does not offer all of the system flexibility that the two motor approach offers and does not comply with one of the requirements originally established for the study, that is, independent shutter speeds and frame rates. Even with this limitation, this approach would offer a significant improvement over current camera design, because it would eliminate the clutch and motor brushes, the two most important objectives of the study.

7. RECOMMENDATIONS

The most significant comparison factors are shown in Table 7-1. The total number of motors used in a camera system with AEC is the same for both approaches because the one motor approach requires a stepper motor for adjusting the variable opening shutter, while the two motor approach requires a stepper motor to drive the shutter.

Based on these factors, if the requirement for independent frame rates and shutter speeds can be removed, the single motor approach is recommended. However, the two motor approach is capable of meeting all of the requirements of the study and should be selected if no deviations can be taken.

TABLE 7-1
Comparison Factors Between the Two Most
Favorable Approaches

| Drive Motors | One | Two |
|--|------|-----|
| Minimum Power | X | |
| Independent Shutter Speeds and Frame Rates | | X |
| Adaptable to Frame Rates Higher than 24 fps | X | |
| Less Remaining Development Effort Required | X | |
| Total Number of Motors, Camera with AEC | Same | |

X = Favorable Factor

APPENDIX A

BRUSHLESS DC MOTORS

APPENDIX A

BRUSHLESS DC MOTORS

The brushless dc motor is of particular interest for application in camera motor drive systems. This term refers to a class of dc motors having neither brushes nor mechanical commutators. Direct current motors of the conventional brush/commutator type have inherent characteristics that impair their usefulness for camera applications, which require reliable, maintenance free operation under harsh and widely varying environmental conditions.

Also, current interruptions, caused by mechanical commutation, create electromagnetic noise which requires, in many instances, additional radio-frequency filtering. Conversely, the life expectancy of the brushless dc motor is generally limited only by bearing lubrication, and at the same time the EMI filtering requirements are not nearly as stringent.

Four distinct types of motors, broadly classified as brushless dc motors are described in the following paragraphs. The differences between these motors are defined primarily in terms of specific design and performance characteristics which ultimately result in their end use application.

ELECTRONICALLY COMMUTATED MOTOR

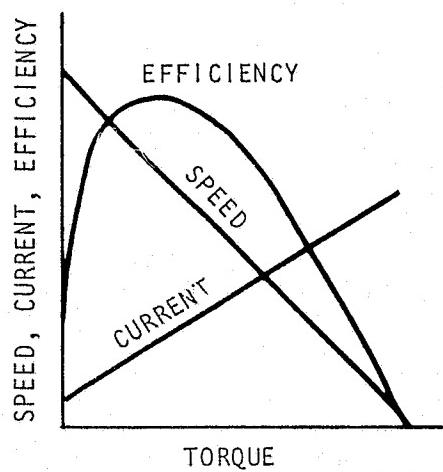
This type of brushless motor substitutes transistor switching circuits for the conventional mechanical commutator. All the linearity and efficiency characteristics of conventional dc motors are exhibited by this device without the problems associated with brushes and commutator bars. Direct, gearless drive capability provides the highest torque to inertia ratio at the load shaft, thereby affording the highest acceleration capability of any motor class.

Position sensors which may be brushless resolvers, Hall effect assemblies utilizing the rotor magnetic field, or assemblies of light source, code wheel and photosensor, control the action of the commutation electronics. The commutation circuits can be either a linear amplifier or saturated switch design, depending on whether or not the application requires precise velocity or position control. The performance characteristics of the electronically commutated dc motor are shown in Figure A-1A.

AC MOTOR/INVERTER

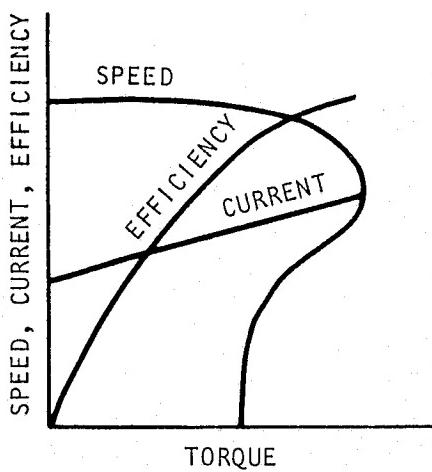
This is a synchronous motor of either the inductor, shaded pole, or hysteresis type with a directly connected dc/ac inverter for conversion to brushless dc operation. External excitation is supplied directly to the rotor field, through

APPENDIX A



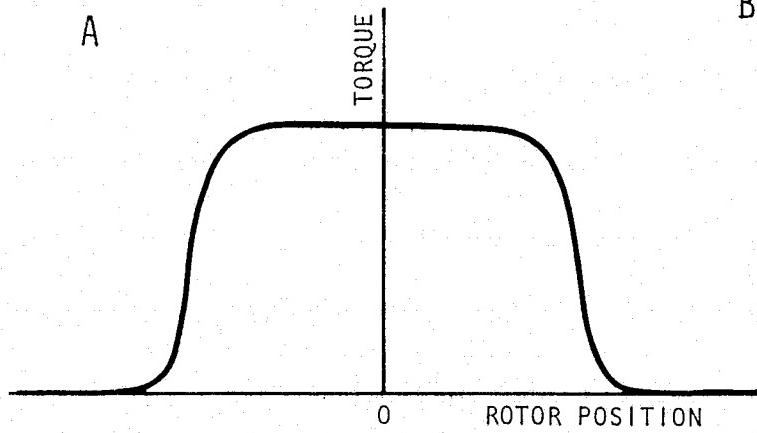
ELECTRONICALLY
COMMUTATED DC MOTOR

A



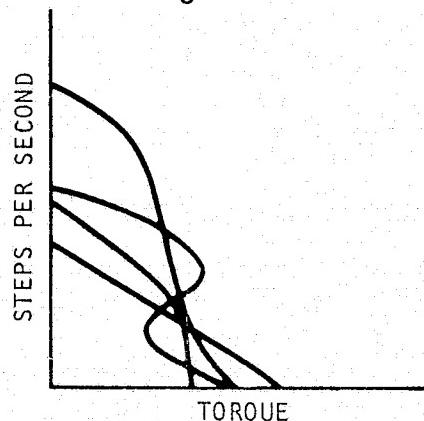
AC MOTOR/INVERTER

B



LIMITED ROTATION DC TORQUER

C



STEPPER MOTOR

D

FIGURE A-1. Brushless DC Motor Characteristic Performance Curves

APPENDIX A

a control circuit consisting of rotor mounted solid state devices. The control circuit excites the motor field to provide constant speed independent of varying load and supply voltage. The motor speed is controlled by adjusting the frequency of the inverter.

Although larger and generally not as efficient as the electronically commutated dc motor, the relatively constant speed of the synchronous ac motor/inverter, without the necessity of external speed control, is more desirable for many applications. However, controlling the speed over a wide speed range is difficult due to inherent characteristics of ac motors. The performance characteristics of the ac motor/inverter are shown in Figure A-1B.

THE LIMITED ROTATION DC TORQUER

This device is a precise, limited rotation actuator that does not require commutation electronics, but does require speed and position feedback to achieve accurate positioning. It is characterized by infinite resolution and continuously linear torque output over a specific angular position or rotor displacement. These motors are constructed with a permanent magnet rotor and a toroidally wound stator, and operate with smooth step free torque. In addition to providing virtually unlimited service life, they provide high peak torque, low power drain, and precise angular resolution. Power is not dissipated in a fixed field phase, when no torque is being delivered. When used over their proper angular range, brushless dc torque motors provide the highest linearity, resolution, efficiency and reliability of any motor obtainable. However, the concept of a noncontinuously rotating motor does not appear readily applicable to a drive system for a sequential space camera.

The performance characteristics of the limited rotation dc torquer are shown in Figure A-1C.

THE STEPPER MOTOR

This digital type of motor converts electrical pulses applied to the windings into discrete stepping movements so that the position of the shaft is directly proportional to the number of pulses applied.

Stepper motors are known by a variety of other functionally oriented names and include: step servo motors, since they fit readily into servosystems; brushless dc motors, since they are constructed without brushes; ac synchronous motors, since with wave shaping and sequencing circuitry they can operate synchronously with an ac input; digital to analog converters, since shaft angle is proportionate to the sum of input pulses received; rotary solenoids, since they have been used to replace conventional rotary solenoids to obtain higher response or reliability; incrementing motors, since the shaft increments through some discrete angle for each input pulse received; and digital output transducers, because of their inherent compatibility with digital systems. Steppers are generally classified as either permanent magnet or variable reluctance types.

APPENDIX A

The permanent magnet (PM) stepper utilizes the reaction between an electromagnetic field and a permanent magnet rotor. In its simplest form, the PM unit consists of a two-pole permanent magnet rotor revolving within a four pole slotted stator. Rotor inertia is generally higher than for variable reluctance steppers. The PM designs offer lower stepping rates than the variable reluctance types, but usually can provide higher rotational speeds because the steps are larger. Further, the PM motors exhibit a strong holding torque with windings energized, and a smaller detent torque when not energized.

The variable reluctance (VR) stepper uses a ferromagnetic multitoothed rotor in interaction with an electromagnetic stator. The exact increment of motor step angle is the difference in angular pitch between stator and rotor teeth. Since the VR motors step angles are small, finer resolution is possible than with PM types. Response rates, in steps/second, are generally higher than for PM steppers.

Both types of stepper motors offer significant advantages when operated open loop compared to the usual closed loop analog servo. Feedback is not ordinarily required, although steppers are compatible with feedback signals, error is non-cumulative as long as pulse to step integrity is maintained. A stream of pulses can be counted into a stepper and the final shaft position is known within a very small percentage of one step. When the desired position is reached and command pulses cease, the shaft stops without requiring clutches and brakes. Once stopped, the motor resists movement up to the value of the stall torque.

An additional feature of the PM stepper is that when all power is removed, it is magnetically detented in the last position. Steppers are inherently low velocity, a typical 15° stepper driven at 500 pulses per second turns at 1250 rpm. Larger stepping angles are generally offset by lower maximum stepping rates. The rotor moment of inertia is usually low. Multiple steppers driven from the same source maintain perfect synchronization.

Some of these advantages are offset by certain disadvantages. Efficiency is low and much of the input energy must be dissipated as heat. Loads must be analyzed carefully for optimum stepper performance. Electrical inputs must also be matched to the motor and load. Resonance can be a problem with VR motors and in some instances with PM, or special PM types when load inertia is exceptionally high. Damping may be required in these instances.

The torque/speed characteristics of stepper motors are highly dependent on the electrical and magnetic design and therefore vary widely. Typical curves are shown in Figure A-1D.

APPENDIX B

SINGLE MOTOR DRIVE

APPENDIX B

SINGLE MOTOR DRIVE

In considering a single motor drive, the inertial and frictional loads placed on the motor must be carefully analyzed. These loads, estimated for a typical 16 mm sequential space camera configuration (see Section 2, Figure 2-1) are presented in Figure 2-2.

Once these loads have been firmly established in the study, various approaches for accomplishing the film pull-down cycle can be examined relative to a specific motor. Four different timing methods which could possibly accomplish the frame rate of 24 fps cine mode, as well as the pulse mode operation, are shown in Figure B-1. A 15° stepper motor is used for discussion purposes, and to simplify Figure B-1, shutter opening and closure are each represented by 180° of mechanical rotation of the motor shaft, twelve 15° steps, for all four modes. Therefore, one complete revolution of the motor shaft is equivalent to one complete film pull-down cycle.

COMBINATION 1

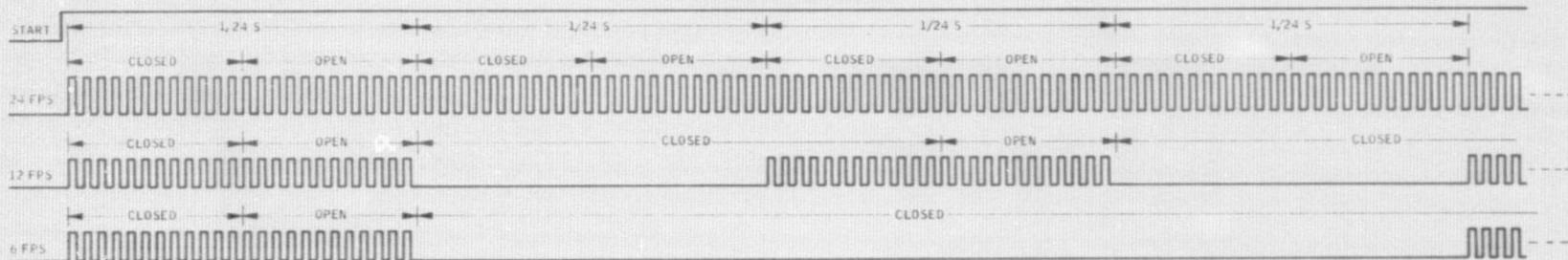
This technique uses a single 576 Hz clock source to drive the stepper motor at 24 revolutions per second. For operation of a frame rate of 24 fps, the shutter starts almost instantaneously from a closed position, rotating 180°, closely followed by 180° open, equivalent to twelve 15° steps, repeating the cycle as many times as desired. During the 180° closure, a claw mechanism, mechanically driven from the same stepping motor, pulls the film to a new stationary position in preparation for the next exposure. The claw retracts during the shutter open time. During both half cycles, the film is continuously fed and taken up by sprockets and the take-up film roll, also driven by the same motor. For slower frame rates, a burst of 24 steps would be applied, followed by an appropriate dwell time with the shutter closed; the exact dwell time would be determined by the particular frame rate desired. The 24 step burst provides constant exposure, independent of frame rate.

This mode of operation places severe inertial load drive requirements on the motor, and assumes the motor can attain the desired speed within 1/576 second without loss of step integrity. Steppers are available which meet this fast response requirement; however, the size, weight and power consumption of a motor that can drive the required inertial load may make this approach prohibitive.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

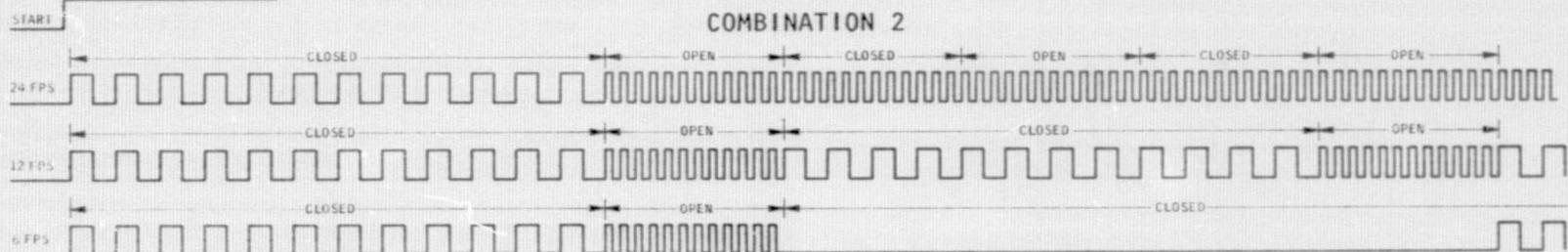
CLOCK RATE = 576 Hz 24 (150 STEPS) / FRAME

COMBINATION 1



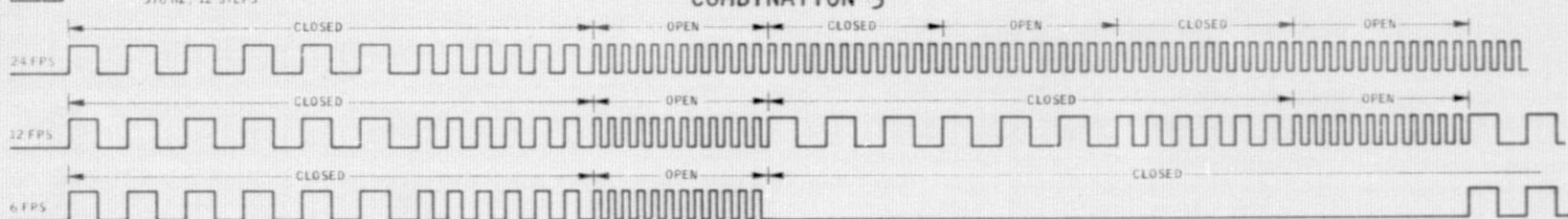
CLOCK RATE = 192 Hz AT START; SWITCH TO 576 Hz FOR 12 STEPS

COMBINATION 2



CLOCK RATE
144 Hz, 6 STEPS
236 Hz, 6 STEPS
376 Hz, 12 STEPS

COMBINATION 3



72 Hz, 6 STEPS
144 Hz, 6 STEPS
236 Hz, 12 STEPS
FOR 24 FPS THEN
SWITCH TO 576 Hz

THESE ASSUME EXPOSURE TIME
BASED ON 12 FPS RATE

COMBINATION 4

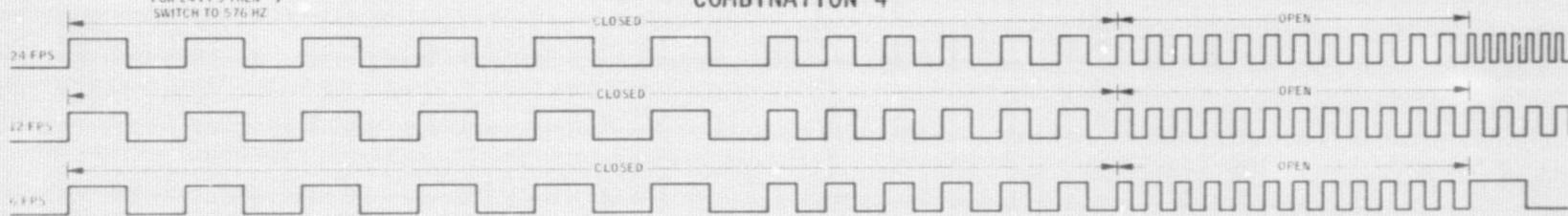


Figure B-1. Four Stepper Motor Timing Methods for Accomplishing the Film Pull-Down Cycle

COMBINATIONS 2 AND 3

These methods reduce the inertial loading demands on the motor while still achieving the correct frame rate and constant exposure time. In combination 2, the motor accomplishes the first 180° of shutter rotation, closed time, at a reduced rate of 192 steps per second, (sps) and then switches to a 576 sps rate for the next 180° of shutter rotation, exposure time. If a frame rate of 24 fps is desired, the motor switches back to 192 sps at the end of exposure, and then repeats the same cycle, alternating between 192 and 576 sps. For all slower frame rates, the motor is totally stopped during part of each cycle, which otherwise is the same as the frame rate of 12 fps cycle.

Combination 3 operation is very similar to combination 2 except a three step frame rate sequence of 144/288/576 sps is used for start up. Combinations 2 and 3 would not only reduce the acceleration demands on the motor compared to combination 1, but would also provide an identical start up, independent of the frame rate selected.

COMBINATION 4

Combination 4 allows longer time for start up and pulse mode operation based on a frame rate of 12 fps rather than a frame rate of 24 fps. The two basic advantages of combination 4 are the further reduction of acceleration requirements, and the lower maximum stepping rate demanded of the motor. For a frame rate of 24 fps, the first frame would be taken at a frame rate of 12 fps, after which the motor would be driven at a frame rate of 24 fps in a continuous non-stepping mode. At a frame rate of 12 fps, the start up would be identical, but the frame rate of 12 fps would continue for the duration of the 12 fps command, similar to the frame rate of 24 fps in combination 3. For a frame rate of 6 fps, the timing cycle would be the same as combination 3 at a frame rate of 12 fps but the stepping rates would be cut in half. The basic disadvantages of this technique is that a shutter opening equivalent to 1/1000 second exposure could not be achieved in the pulse mode.

However, the advantages of reduced acceleration relative to the inertial loading requirements may more than balance out the loss of 1/1000 second exposure for pulse mode, single shot, operation.

Functionally, the various building blocks required to perform the start up and run techniques described in the previous paragraphs, are shown in Figure B-2. The oscillator provides the primary clock frequency. The clock profile generator consists of two to four binary counters, and any decoding logic necessary to provide a selected start up profile. The motor drive logic consists of a ring counter and the necessary switching transistors to properly sequence the motor.

In the event of a power failure in the middle of a cycle, a coarse position indicator would be desirable. This would simply provide the quadrant in which the motor has been stopped so that when the camera is retriggered, the motor can be synchronized to the proper point in the operating cycle. As indicated in Figure B-2, the shutter and claw are driven directly by the stepper motor, whereas the take up and feed are driven through an appropriate gear reduction.

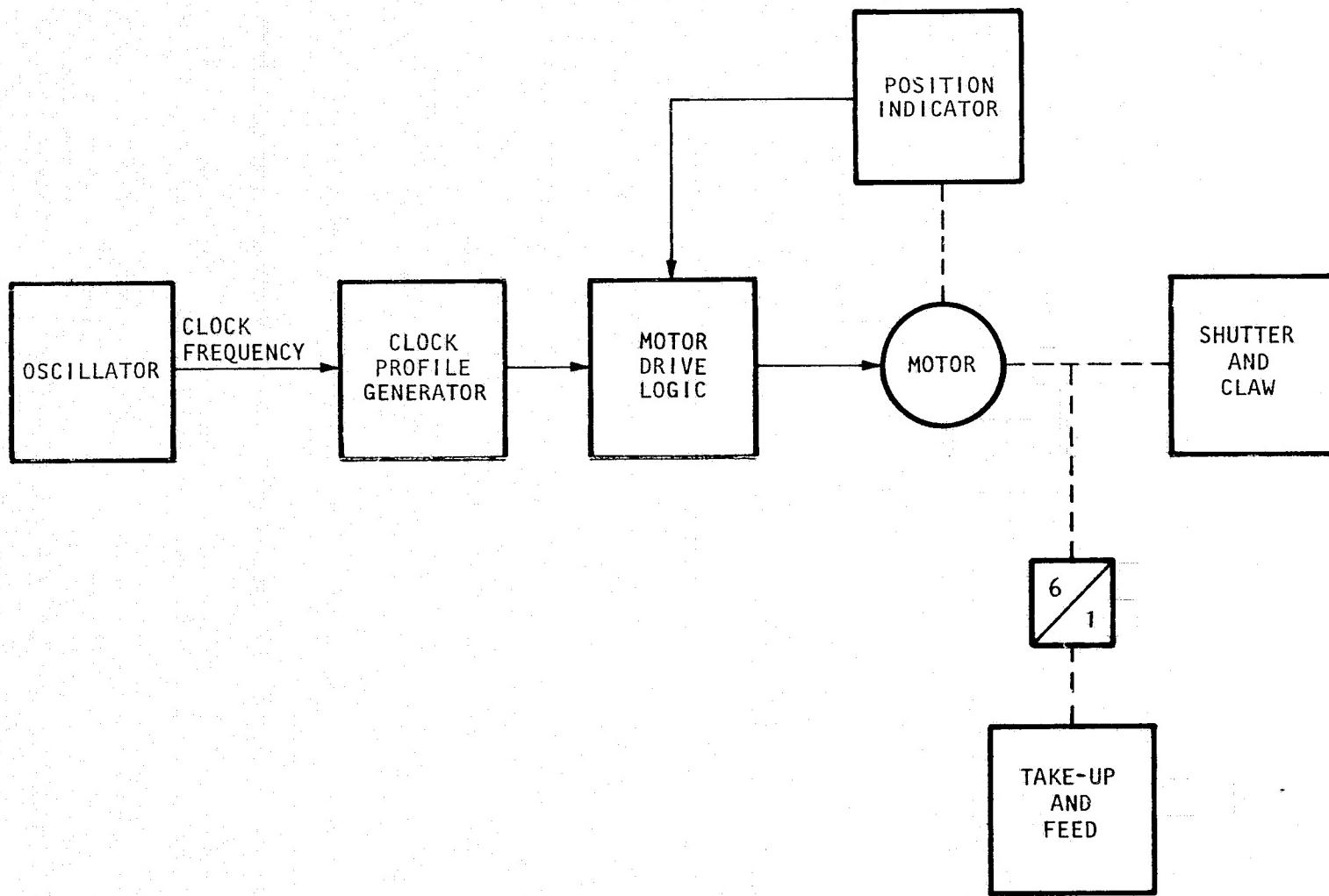


FIGURE B-2. Single Motor Drive Functional Block Diagram